EVALUATION OF THE IMPACT OF CONTROLLED TILE DRAINAGE ON SURFACE WATER QUALITY IN THE SOUTH NATION RIVER WATERSHED

by

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DEDICATION

This thesis is dedicated to my parents, Que Jushan and Ma Zhenrong, for their inspiration and devotion to my education from my childhood, and specifically to my wife, Ni Peihong, for her sacrifice to our family. Without their support and help, this thesis would not have been completed.

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ABSTRACT

In Ontario, Canada, many agriculture-dominated watersheds are experiencing ecosystem deterioration because of non-point source pollution mainly resulting from agricultural activities. Sediment, nitrogen and phosphorus from agricultural areas can drive water quality parameters below acceptable limits. The South Nation River watershed (SNW) located in eastern Ontario, which is such a highly cultivated watershed with relatively dense population compared to other areas in Canada, is an example of them. The historical trend of total nitrogen loading in its surface waters has revealed a remarkable increase since the 1960s (Fleming et al., 1999) and total phosphorus concentrations regularly exceed the provincial water quality objective of 0.03 mg/L (SNC, 2006).

One way to reduce pollutant loads in water bodies is to implement agricultural best management practices (BMPs), which are optimized agricultural management operations and techniques adopted to reduce pollutant loads to streams. A common practice is uncontrolled tile drainage (UCTD) where the water level in the field is reduced by a series of buried pipes (drains) to permit earlier seeding, efficient use of fertilizer, and a substantial increase in crop yield. A BMP alternative to UCTD is controlled tile drainage (CTD) where the water table is managed through a controllable facility on the field. In practice, CTD maintains water and nutrients in the field and releases them in an intermittent manner, when available storage in the drains is exceeded. Research has shown that CTD is a promising BMP capable of improving water quality and crop yields by reducing water and nutrient losses from tile-drained fields.

A national project aiming to evaluate the performance on water quality of agriculture BMPs at watershed scale, The Watershed Evaluation of Beneficial Management Practices (WEBs), had been carried out from 2004 by Agriculture and Agri-Food Canada (AAFC). One activity of the WEBs project consisted of applying CTD and UCTD on two micro-watersheds in the SNW. A comprehensive data collection program was also designed to systematically collect hydrological, agricultural and water quality parameters in the experimental fields and in surrounding water bodies. Preliminary analysis of the collected data shows significant reduction of nutrient loads and improved crop yield in CTD-treated fields versus UCTD-treated fields, and suggests that an upscaling of CTD to the entire watershed (where applicable) can be economically viable while improving surface water quality in the watershed.

The primary objective of this thesis is to find out how much water quality improvement can be expected if CTD was adopted by farmers at watershed scale. A watershed model, AnnAGNPS, was therefore applied, calibrated and validated on the watershed. The model performance during the calibration and validation periods was assessed using the Nash-Sutcliffe model performance criteria, and the values obtained compare favourably to typical values found in the literature. AnnAGNPS was afterward used to simulate water quality under two scenarios where UCTD and CTD were applied to all croplands where these practices were applicable. Implementation of CTD and UCTD in the model was carefully calibrated on the basis of observations from WEBs project experimental sites in the SNW. Simulations were restricted to growing seasons, from May to November of 2006 and 2007 in line with observations from a field study in the watershed (WEBs project).

When compared to the outputs from the UCTD scenario, the CTD scenario leads to 2.70, 2.11, and 32.2 reduction rates of runoff, sediment and nitrogen, respectively. Results indicate that CTD can significantly improve surface water quality by reducing nitrogen losses from agricultural areas in a watershed. Compared to the reduction of nitrogen, reductions of runoff and sediment appear marginal. However, these reductions are also considerable regarding them only from potential CTD fields and their huge absolute values.

This shows that the CTD can effectively prevent nitrogen export from crop fields to steams, sequentially alleviating surface water pollution. However, reductions of phosphorus, –0.82%, yields to streams do not match the actual observations from the field study, allegedly because of the poor simulation by AnnAGNPS of major dissolved phosphorus processes in the model.

This research creatively uses the AnnAGNPS model to simulate CTD, and it also provides a reliable link of the tile drainage rate (TDR) of the model to observations from experimental CTD fields. So far, there is no related research found from the literature.

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LIST OF ABBREVIATIONS

AAFC	Agriculture and Agri-Food Canada
ADMSTF	Agricultural Drainage Management Systems Task Force
AGNPS	Agricultural Non-Point Source model
AnnAGNPS	Annualized Agricultural Non-Point Source model
ANSWERS	Areal Non-Point Source Watershed Environmental Response Simulation
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
ARS	Agricultural Research Service
BASINS	Better Assessment Science Integrating point and Non-point Sources
BMP	Best management practice
CN	Curve number
CREAMS	Chemicals, Runoff and Erosion from Agricultural Management Systems
CRM	Coefficient of residual mass
CSA	Critical source area
CTD	Controlled tile drainage
DR3M	Distributed Routing Rainfall Runoff Model
DEM	Digital Elevation Model
E	Nash coefficient of efficiency
EI	Energy intensity
EOWRMS	Eastern Ontario Water Resources Management Study
EPA	Environmental Protection Agency
FR	Fertilizer rate
GEM	Generation of weather elements for multiple applications
GIS	Geographic Information System
K	K factor
K_{sat}	Saturated hydraulic conductivity
MIKE-SHE	European Hydrological European
MSCL	Minimum source channel length
n	Manning’s roughness coefficient
N	Nitrogen

NRCS	Natural Resources Conservation Service
NU	Nitrogen uptake
OMR	Organic matter ratio
OMNR	Ministry of Natural Resources
PWQMN	Provincial Water Quality Monitoring Network
P	Phosphorus
PS	Point source
PU	Phosphorus uptake
R	Rainfall factor
RMSE	Root mean square error
RUSLE	Revised universal soils loss equation
SCS	Soil Conservation Service
SHE	European Hydrological System
SI	Sensitivity indicator
SNC	South Nation Conservation
SNW	South Nation River watershed
STEAD	Summarization tool to evaluate AnnAGNPS data
STD	Standard deviation
SWRRB	Simulator for Water Resource in Rural Basins
SWAT	Soil Water Assessment Tool TDR Tile drain rate
TOPAZ	Topographic Parameterization
UCTD	Uncontrolled tile drainage
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WHAT	Web based Hydrograph Analysis Tool
WEBs	Watershed Evaluation of Beneficial Management Practices

CHAPTER 1

INTRODUCTION

1.1 Study Area

The SNW (Figure 1) is located in eastern Ontario, Canada and covers an area of approximate 3800 km^2 between 44°44´- 45°38´ N latitude and 75°32´- 74°22´ W longitude. The South Nation River rises from its source in the north of Brockville, and flows 175 km northeast as a tributary to the Ottawa River near Plantagenet.

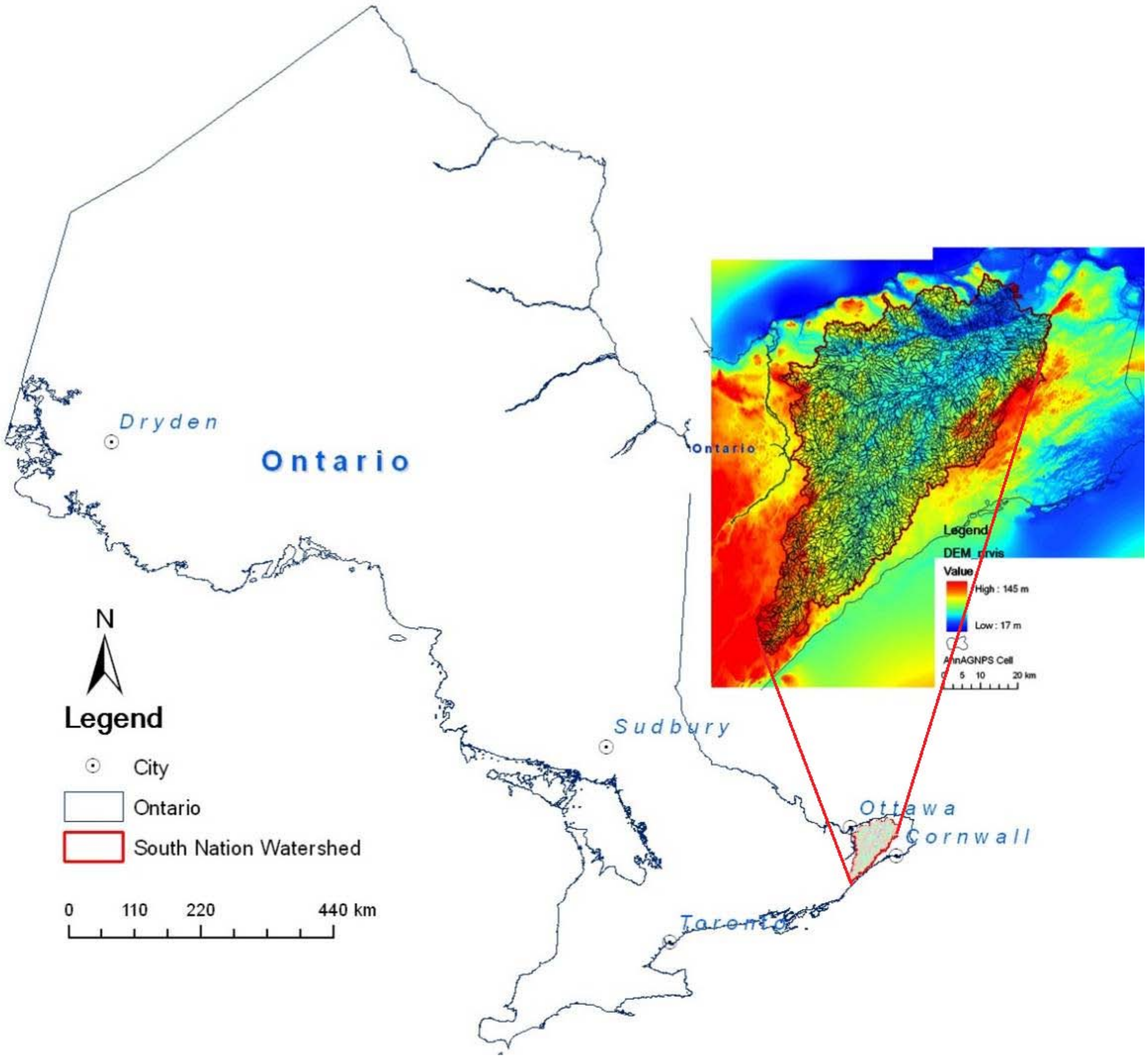


Figure 1 Location of the South Nation watershed

The name of the river originated from the native people in this area. There are several main tributaries, North Branch South Nation River, Payne River, and Castor River, contributing to the river. Maximum discharge generally occurs in April resulting from snow melt. The topography of the watershed is relatively flat with an average slope of ~0.05%. Agriculture is the dominant land use in the watershed (~60%) with mixed urban (~5%), and natural (wooded/shrub) (~34%) land uses. Soils are predominantly clay. Tile drainage exists for approximately 43% of the arable lands in Ontario (Vanderveen, 2001). The average annual precipitation is about 733 mm. Climate in the region is temperate with average monthly temperatures varying between −15 to 22°C.

1.2 WEBs Project

In 2004, Agriculture and Agri-Food Canada (AAFC) launched the Watershed Evaluation of Beneficial Management Practices (WEBs), which is a national project which aims to evaluate the performance (within a water quality context) of selected agriculture beneficial management practices (BMPs) at the watershed scale. The project consists of applying selected BMPs on micro-watersheds, intensive data collection.

The WEBs watershed in Ontario is situated in the SNW. Two micro-watersheds within the watershed, each about 450 ha are the experimental sites. Within the two micro-watersheds, the effects of two BMPs, controlled tile drainage (CTD) and uncontrolled tile drainage (UCTD), is being evaluated to determine whether controlled drainage effectively reduces pollutant inputs (primarily nitrogen) to streams while at the same time improving crop performance. Through the WEBs project from 2005 onwards, a large amount of valuable experimental data has been gathered that was used in this research.

1.3 Statements of Problem

Water is essential to all life forms, and maintaining water quality is of crucial importance to support sustainable ecosystems. However, human activities often have negative impacts on water quality and impair aquatic ecosystems. There are mainly two types of sources of pollution, point source (PS) pollution resulting from pollutants issued by industrial facilities, municipal treatments plants, other point sources and non-point sources (NPS) caused by diffuse sources such as agricultural areas.

In Ontario, Canada, many watersheds are threatened or exhibit severe ecosystem deterioration because of pollution mainly resulting from agricultural activities. The SNW is such a highly cultivated watershed with relatively dense population compared to other areas in Canada, is an example of them. The historical trend of total nitrogen loading in surface water has revealed remarkable jumps since the 1960s (Fleming et al., 1999); total phosphorus concentrations regularly exceed 0.03 mg/L which is the provincial water quality objective (SNC, 2006).

Water pollution associated with agricultural activities can be reduced through BMPs which optimally manage agricultural operations and techniques known to be capable of significantly preventing pollutants from reaching streams. BMPs can be employed to help alleviate surface water pollution (Parker et al., 2008) in the SNW. In tile drained landscapes, CTD has shown promise.

Nevertheless, most studies have examined the impact of CTD on tile drainage and surface water quality at field or plot level; there is a dearth of information on watershed level effects.

1.4 Research Objectives

This research intends to assess CTD effects on surface water quality at watershed scale with CTD and UCTD scenarios designed on the basis of experimental data collected from the WEBs project; hence, it could help assess and improve surface water quality in agricultural watersheds throughout Canada.

1.5 Approach

Due to the high expense and time demanded to run experiments and collect observations at watershed scale, specifically for a large scale watershed such as the SNW, the only appropriate method to evaluate impacts of CTD is via modeling. This research takes advantage of the dynamic pollutant loading model, Annualized Agriculture Non-Point

Source (AnnAGNPS), which incorporates computer and GIS technologies involved soil, hydraulics, hydrology, water chemistry, meteorology, agriculture and etc.

In the initial phase of this research, datasets collected from two experimental micro-catchments of the WEBs project were analysed, and this information was used to help populate a river watershed model to assess the impact of CTD on surface water quality and quantity. Then the continuous-simulation AnnAGNPS model was calibrated and validated with the observed data for runoff, sediment, nitrogen, phosphorus and other required data in the SNW. Finally the impacts of applying the CTD scenario to all fields with a suitable slope for building CTD facilities were evaluated. Runoff, sediment, nitrogen and phosphorus impacts on the entire watershed were evaluated.

In order to achieve the above principal objective, the following milestones were identified:

- Review of available watershed-scale hydrological NPS pollution models to identify their applicability to this research;
- Prepare input datasets for the continuous-simulation AnnAGNPS model (climate, crop, fertilizer, land use, management, pesticide, soil, tile drain and topographic data);
- Populate, calibrate and validate a sound model of the watershed using AnnAGNPS;
- Analyze the data sets collected from the two experimental micro-catchments of WEBs project and use this information;
- Identify areas where CTD can be applied based on the existence suitable slope for building CTD facilities and develop CTD and UCTD implementation scenarios;
- Evaluate the impacts of applying the CTD scenario to the potential of CTD fields in terms of runoff volume and sediment, nitrogen and phosphorus loads in the South Nation River;
- Issue preliminary recommendations and develop the data sets necessary for a cost-benefit analysis of CTD implementation for other teams in the WEBs project.

CHAPTER 2

WATERSHED HYDROLOGIC AND NON-POINT SOURCE POLLUTANT MODEL REVIEW

Currently, there are numbers of promising models that can be applied to NPS pollution evaluation at watershed level such as the Agricultural Non-Point Source pollution model AGNPS (Young et al., 1989), AnnAGNPS (v4.00.a.019) (Bingner et al., 2007), Areal Non-Point Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al., 1980), ANSWERS-2000 (Bouraoui et al., 1996), Better Assessment Science Integrating point and Non-point Sources (BASINS) (USEPA, 2008), the European Hydrological System model (MIKE-SHE) (Graham et al., 2005), and Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Winchell et al., 2005). These models are reviewed in the following sections.

2.1 AGNPS and AnnAGNPS

AnnAGNPS (Bingner et al., 2007) was developed by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) and Natural Resources Conservation Service (NRCS). It is a comprehensive computational simulation model evolved from AGNPS (Young et al., 1989) designed for evaluating NPS pollutant loads in watersheds dominated by agriculture. Besides inheriting most properties from AGNPS, AnnAGNPS incorporates more updated emerging features and introduces more parameters and capabilities to be capable of simulating complex situations in flexible conditions. Briefly, AnnAGNPS is a distributed simulation model that subdivides a watershed into small homogeneous sub-watersheds that are named cells in the model. Cells are afterward interconnected by stream channels called reaches. Runoff generation in cells is based on the USDA Soil Conservation Service (SCS) curve number (CN) method while sediment yields are calculated using the revised universal soils loss equation (RUSLE) (Renard et al., 1997). Also, simplified nutrient cycles such as nitrogen and phosphorus that focus on major nutrient movements are implemented in AnnAGNPS.

2.2 ANSWERS and ANSWERS-2000

The original ANSWERS (Beasley et al., 1980), which emerged at Purdue University in Indiana in the late 1970s, is an event-based evaluation physical model that adopts distributed parameters such as climate data, land use, soil, nutrients, crops, and management practices to simulate impacts of BMPs on agricultural watersheds. On the basis of ANSWERS, ANSWERS-2000 (Bouraoui et al., 1996) extends the simulation capability from event-based storms to long-term continuous annual runoff, sediment and nutrition loadings. Like AnnAGNPS, ANSWERS-2000 provides an ArcView interface in order to facilitate data preparation. The model is suitable for being applied to watersheds that are short of observed data for model calibration.

2.3 BASINS

BASINS (USEPA, 2008) is an environmental assessment tool designed for several purposes such as facilitating examination of environmental information, supporting analysis of environmental systems and providing a framework for examining management alternatives. From 1996, it has been used by researchers to analyze effects of PS and NPS pollution on water quality in watersheds. After years of improvements, it has a sophisticated graphical user interface based on open-source GIS architecture equipped with support of hydrologic and monitoring data via the link to the BASINS website.

2.4 MIKE-SHE

On the basis of the European Hydrological System (SHE) (Abbott et al., 1987a, 1987b), MIKE-SHE (Graham et al., 2005) developed by the Danish Hydraulic Institute, the French consulting firm, SOGREAH, and the UK Institute of Hydrology is a physically based, distributed parameter watershed model applied to simulate surface water groundwater, watershed management and planning, assessment of impact on environment, impact of changes in land use and climate on watershed, impact of agricultural practices such as drainage, nutrients and others. It is not only capable of simulating single-storm events but also continuous long-term patterns.

2.5 SWAT

SWAT (Arnold et al., 1998; Winchell et al., 2005) inherits its main features from Simulator for Water Resource in Rural Basins (SWRRB) (Williams et al., 1985; Arnold et al., 1990), Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980), Groundwater Loading Effects on Agricultural Management Systems (GLEAMS) (Leonard et al., 1987), Erosion-Productivity Impact Calculator (EPIC) (Williams et al., 1984) and Routing Outputs to Outlet (ROTO) (Arnold et al., 1995). Over more than thirty years, SWAT has evolved into a broadly adopted tool for evaluating the impact of land management practices on water, sediment, nutrient loadings, pesticide and bacteria within a watershed. It consists of eight major components: agricultural management, crop growth, hydrology, nutrients, pesticides, sedimentation, soil temperature, and weather. It is both a physically based and computationally efficient model developed for long-term continuous simulations, whereas it is not suitable for detailed single-event flood routing.

2.6 Summary

Computational models simulating complicated hydrological processes in nature are powerful aids to researchers, whereas building a realistic model that can well characterize hydrological processes is a large challenge to developers because of their complexities resulting from numerous interactional factors. Moreover, for a specific watershed with different conditions and research objective, there is no a general model that can meet all needs or applications.

Although these five models are all well developed and qualified generally, AnnAGNPS has obvious advantages such as open source code, plenty of supporting documents, successful applications all over world, and reachable online technical help form the model developer. Compared to the other four models, the important advantage is that this model provides tile drain parameters which allow simulating the experimental CTD facility in WEBs project. In view of these advantages, AnnAGNPS was chosen as the appropriate model for this research.

CHAPTER 3

AnnAGNPS AND SENSITIVTY ANALYSIS

3.1 AnnAGNPS Model

3.1.1 Components of the model

From release of the AnnAGNPS version 1.00 on the basis of AGNPS 5.0 and RUSLE in February, 1998 to the version 4.00.a.019 issued in July, 2008, with years of updating and extending, the model has been grown up to a fully functional pollutant loading modeling software package shown as Figure 2.

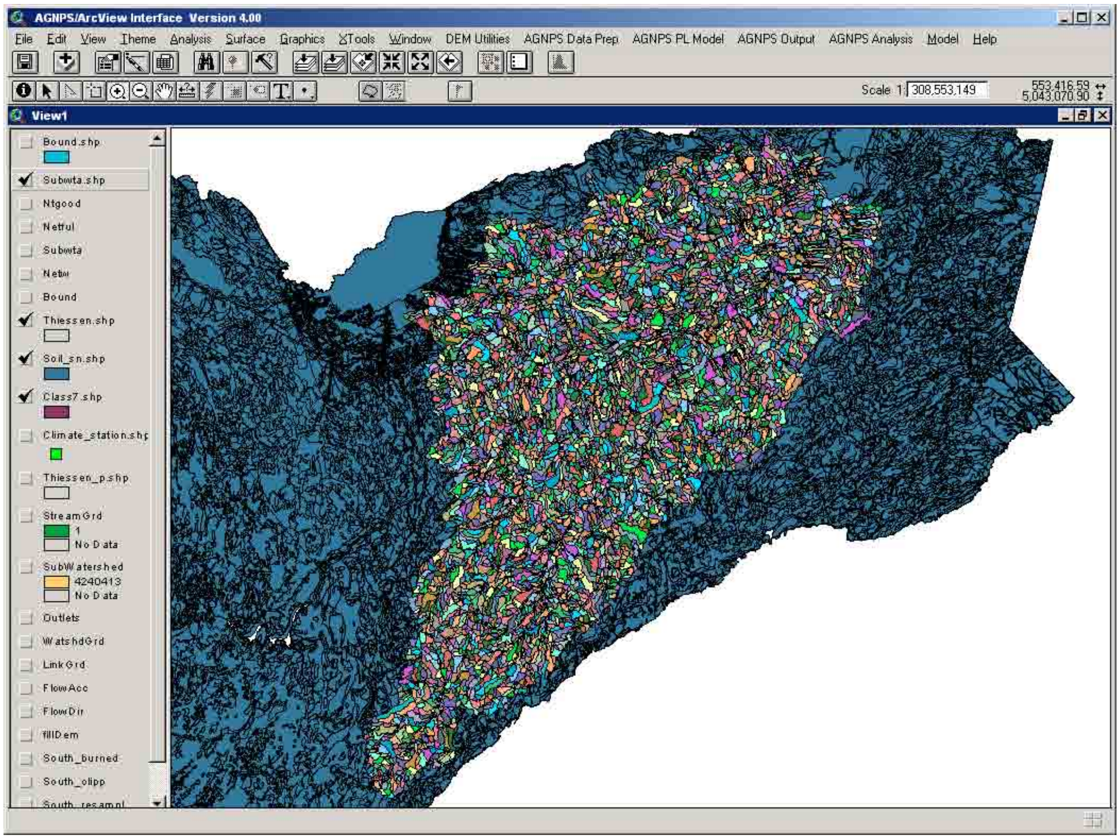


Figure 2 AnnAGNPS model incorporated in ArcView

According to function classification, the model can be divided into three relatively independent modules: input preprocessing module, main calculating module and output postprocessing module. The components of AnnAGNPS are shown in Figure 3.

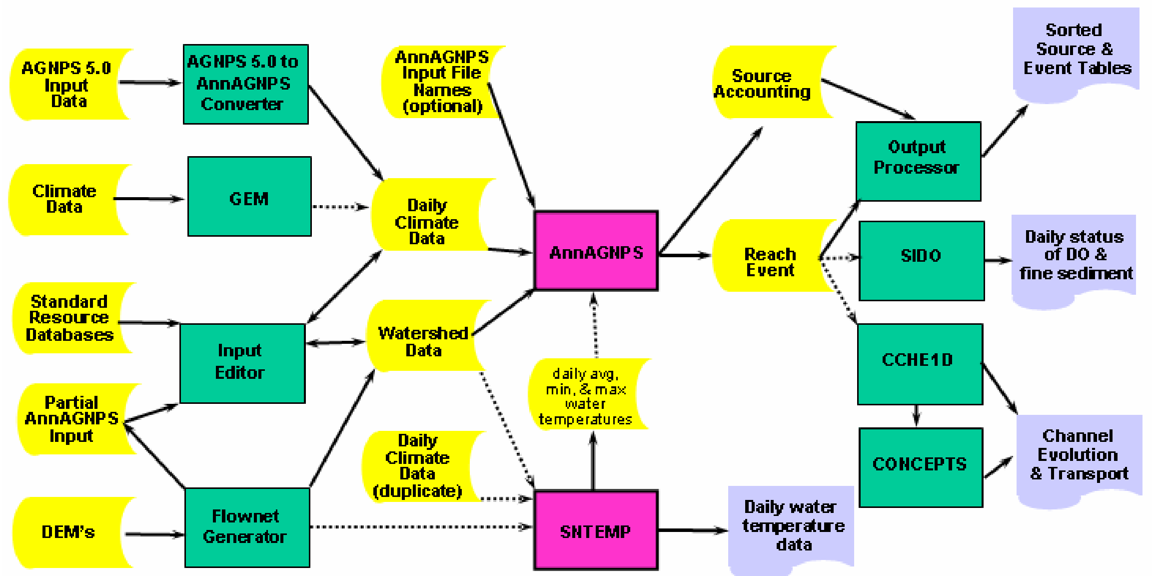


Figure 3 Components of AnnAGNPS model (Bingner et al., 2007)

3.1.1.1 Input preprocessing module

The input preprocessing module contains four components that assist the user to generate new or revise existing AnnAGNPS input datasets.

- AnnAGNPS ArcView Interface shown in Figure 3.1, which incorporates all model components into ArcView, provides an intuitive integrated operating platform to the user. The interface incorporated a software package called TOpographic PArameteriZation (TOPAZ) (Garbrecht and Martz, 1997) which can automatically deal with analysis of digital landscape topography such as a digital elevation model (DEM) which is especially helpful.
- AnnAGNPS Flownet Generator can deal with a DEM and prepare topographic data for the model, but it is not as easy to use as the ArcView interface.
- Generation of Weather Elements for Multiple Applications (GEM) program (Johnson et al., 2000) can generate synthetic climatic data if the user is within the US. Otherwise the user has to rely on a Complete_Climate program to generate climatic data for the model.
- AnnAGNPS Input Editor shown is the key editing tool to create a new or modify input dataset.

3.1.1.2 Main calculating module

This module only contains one stand-alone program coded and compiled in Fortran 90, which is in charge of overall simulation and execution of the AnnAGNPS model. To run the model, the user calls it from either the AnnAGNPS ArcView Interface or a specific folder on the computer. The input data files, commonly named AnnAGNPS.inp and DayClim.inp, are better placed in the current directory; otherwise, the user has to define the path in the AnnAGNPS.fil file informing the model. The output files such as error, debug, and event will normally be put in the current directory.

3.1.1.3 Postprocessing module

Like the main calculating module, the postprocessing module is also a stand-alone program named Summarization Tool to Evaluate AnnAGNPS Data (STEAD). It assists the user to extract specific useful information from the output files generated by the AnnAGNPS program for further summarizing and analysis. For version 4.0, STEAD cannot deal with numbers more than one hundred millions, a program was created to assist the model in calculating annual and monthly outputs (detailed in Appendix D.2).

3.1.2 Major principles in AnnAGNPS

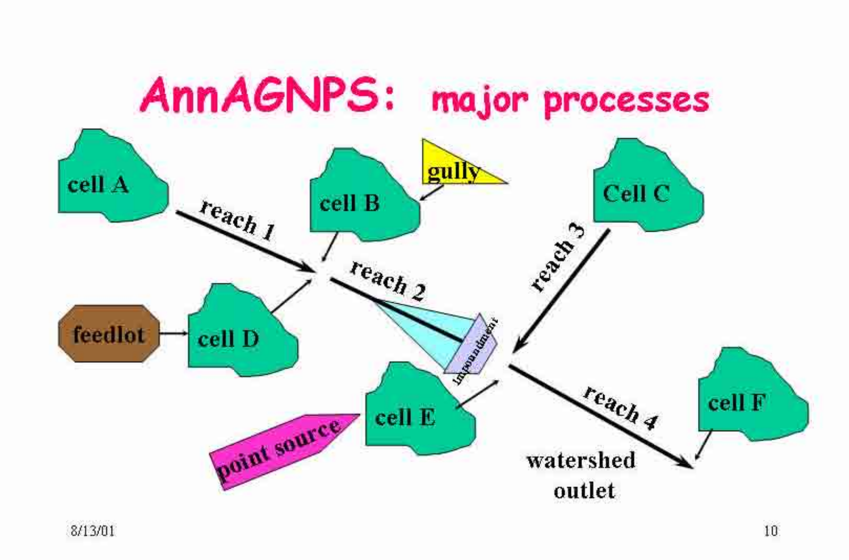


Figure 4 Major processes in AnnAGNPS (Bingner et al., 2007)

Due to the complex of major processes in the model, the model provides hundreds pages of technical documentation to describe the details and background. The following descriptions only demonstrate the major processes in the model.

3.1.2.1 Surface flow

The model adopts the SCS CN method (USDA, 1972) to generate the surface flow from a field. The SCS surface flow equation is

$$Q = \frac{(P - 0.2S)^2}{P - 0.8S} \qquad \text{Equation 3-1}$$

where

Q = surface flow (mm)

P = precipitation (mm) and

S = potential maximum retention after surface flow begins (mm)

S is related to the complex of the soil, vegetation and land use conditions through the CN in a watershed. CN has a range of 0 to 100, and the SCS defined S as a function of CN in the model as

$$S = 254\left(\frac{100}{CN} - 1\right) \qquad \text{Equation 3-2}$$

3.1.2.2 Subsurface flow

The subsurface flow in the model (detailed in Appendix F) comprises tile drainage flow and lateral subsurface flow. The model deploys a Hooghoudt equation to determine tile drainage flow within a field due to its wide applicability and simple structure. The equation is

$$q_{drain} = \frac{8K_s d_e m + 4K_s m^2}{{L_D}^2} \qquad \text{Equation 3-3}$$

where

q_{drain} = tile drainage flow (mm per time period),

K_s = saturated lateral hydraulic conductivity (mm per time),

L_D = distance between drains (m),

m = midpoint water table height above the drain (m),

d_e = equivalent depth of the impermeable layer below the drain (m).

As for lateral subsurface flow, Darcy's equation is used by the model. Its expression is

$$q_l = -K_s \frac{dh}{dl} \qquad \text{Equation 3-4}$$

where

q_l = subsurface lateral flow (mm per time period),

dh/dl = hydraulic gradient.

3.1.2.3 Sediment

In comparison with flow, sediment yield and transport are more difficult to determine and simulate in a field. The model uses the RUSLE to simulate sediment within a field. Theurer and Clarke (1991) defined sediment yield as

$$S_y = 0.22Q^{0.68}q_p^{0.95}KLSCP \qquad \text{Equation 3-5}$$

where

S_y = sediment yield (Mg/ha)

Q = surface runoff volume (mm)

q_p = peak rate of surface runoff (mm/s)

K = soil erodibility

L = slope length

S = slope steepness

C = cover-management

P = support practice

3.1.2.4 Nitrogen

Nitrogen, which is a widely distributed element and the basis of life in nature, can form many important compounds and biological molecules. In order to increase crop production, nitrogen fertilizer is often used in modern agriculture. Agricultural and urban activities are main contributors to non-point nitrogen and phosphorus pollution (Novotny, 2003).

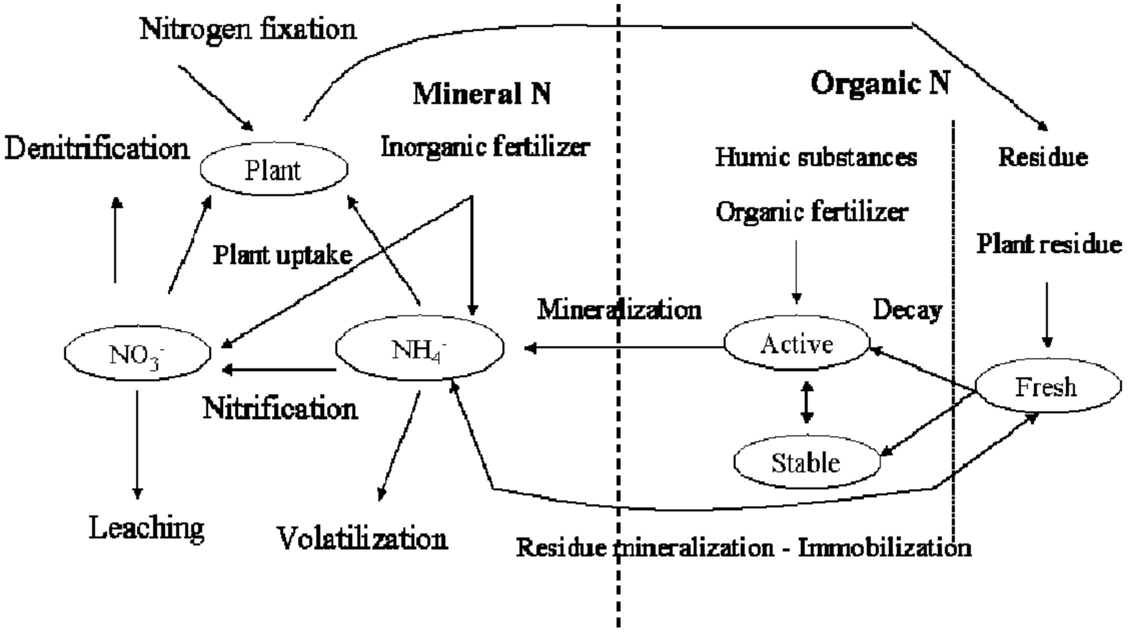


Figure 5 Simplified nitrogen processes in soil (Havlin et al., 1999)

Nitrogen and its compounds have the most complex transformation processes when they participate in the natural cycle (Figure 5). As a result, the model only simulates major nitrogen processes based on organic matter in soil, plant residues, fertilizer inputs and plant uptake. In this model, stable organic N, active organic N (mineralizable N), and inorganic N are considered as shown in Figure 6. Losses (cell output pathways) consist of soluble inorganic N in runoff, leaching, denitrification, and sediment-bound organic N from soil erosion.

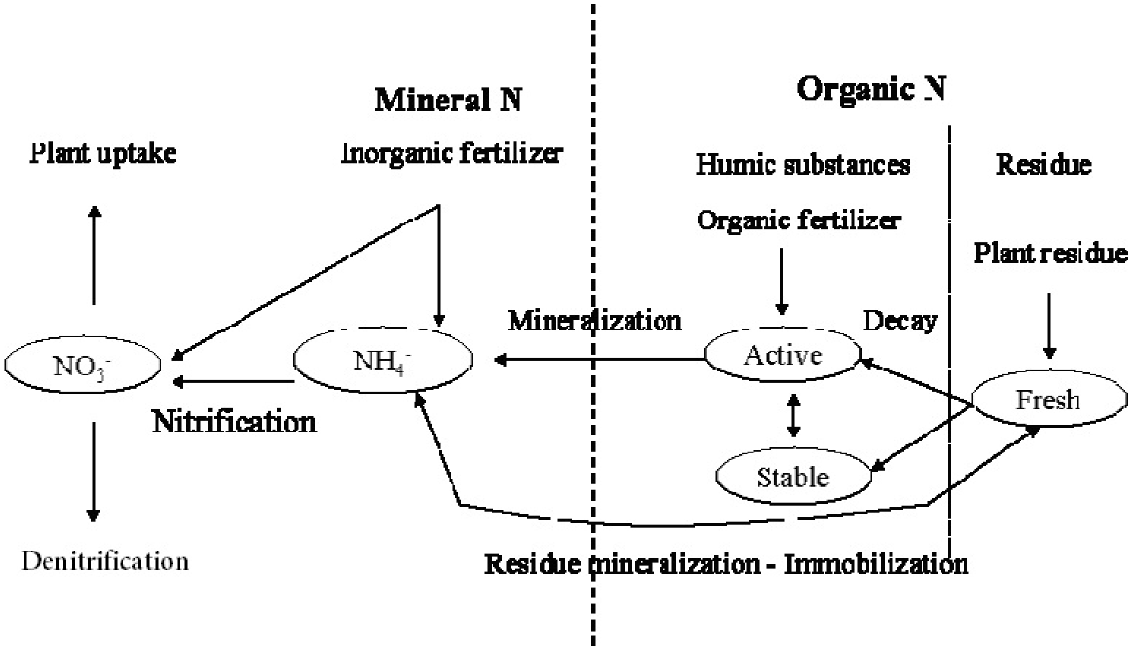


Figure 6 Nitrogen processes simulated in AnnAGNPS (Bingner et al., 2007)

Bingner et al. (2007) described that the organic nitrogen simulation process is

$$N_{ot} = N_{ot-1} + \frac{1000000(N_r + N_f + N_h - N_s)}{conv} \quad \text{Equation 3-6}$$

where

$conv$ = intensive unit to extensive unit conversion factor (kg)

N_{ot}= concentration of organic N in the total composite soil layer for current day (ppm)

N_{ot-1} = concentration of organic N in the total composite soil layer for previous day (ppm)

N_r = organic N addition from decomposition of crop and non-crop residue laying on the soil surface to cell soil layer 1 on the current day, (kg). Non-crop residue refers to nitrogen from litter dry biomass for non-cropland surface residue that is subject to decomposition. Upon decomposition, by-products are considered mixed uniformly in soil layer 1.

N_f = organic N from fertilizer application such as manure or other sources (kg)

N_h = N mineralized from organic N in soil layer on the current day (actual argument passed to inorganic N mass balance subroutine (kg)

N_s = current days mass of nitrogen attached to sediment (kg)

In the model, denitrification is considered as one of major nitrogen losses. For saturated soil, if oxygen is absent or depleted to a point below the oxygen demand, NO_3^- is converted into NO_2, NO, N_2O and N_2 (Bingner et al., 2007). Over a time step:

$$DN = \frac{inorgN * conv}{1000000} * (1 - \exp(-1.4 * F_t * orgC)) \qquad Fw>0.9 \qquad \text{Equation 3-7}$$

$$DN=0 \qquad Fw<0.9$$

Where:

DN = denitrification (kg),

inorgN = amount of nitrate nitrogen in the soil (ppm),

conv = conversion factor,

Ft = nutrient cycling temperature factor, temperature correction factor as used for mineralization,

orgC = organic carbon content (%),

Fw = nutrient cycling water factor, as used for mineralization

Denitrification occurs only when soil moisture content is above 90% of porosity. With CTD condition, this process usually occurs because of retention of water in tiles for a long period.

3.1.2.5 Phosphorus

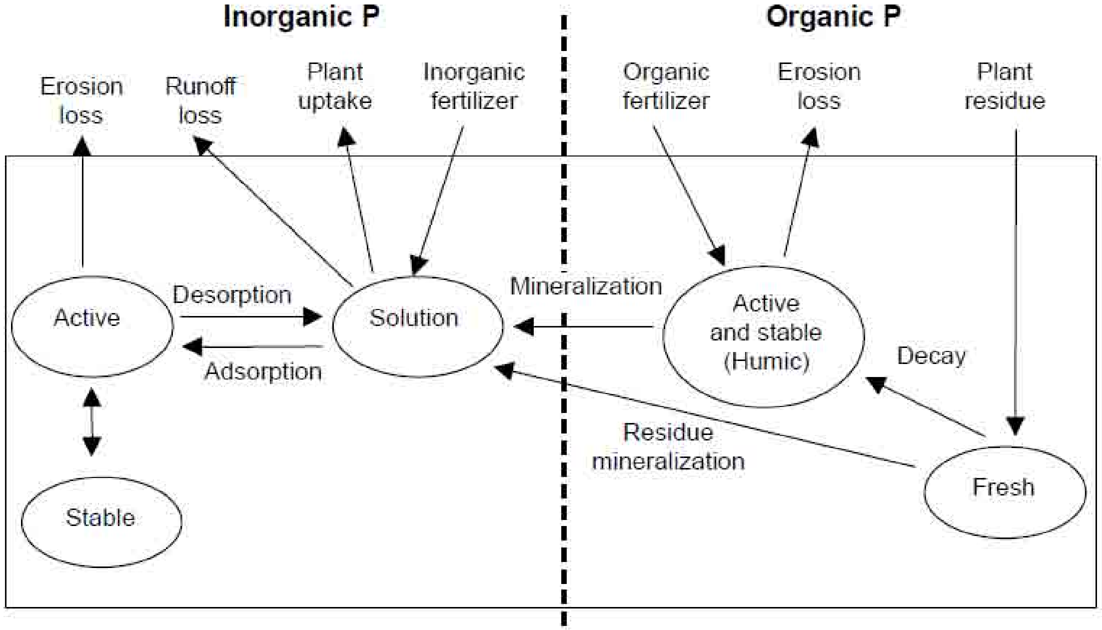


Figure 7 Phosphorus processes in AnnAGNPS (Yuan et al., 2005)

Phosphorus is an essential element to living organisms and widespread in the surface of the earth as the form of phosphates. With more application of phosphorus fertilizer, phosphorus in agricultural soil is increasing and becomes a main cause of pollution like nitrogen. Principal phosphorus processes in AnnAGNPS are shown as Figure 7, and the major phosphorus processes were defined as

$$P_{ot} = P_{ot-1} + \frac{1000000(P_r + P_f + P_h - P_s)}{conv} \qquad \text{Equation 3-8}$$

where

P_{ot} = concentration of organic P in the total composite soil layer for the current day (ppm)

P_{ot-1} = concentration of organic P in the total composite soil layer for the previous day (ppm)

P_r = organic P addition to cell soil layer 1 from decomposed fresh crop residue on the current day (kg)

P_f = organic P from fertilizer application such as manure or other sources (kg)

P_h = mineralization rate from the humus active organic P pool on the current day (kg)

P_s = current days mass of P attached to sediment (kg)

Appendix F provides completed reference for nitrogen and phosphorus calculation in the model.

3.2 Sensitivity Analysis

Sensitivity analysis can be used to evaluate the influence of input data error and predict the sensitive parameters of a model (McCuen, 1973). All phases of hydrologic modeling can benefit from sensitivity analysis, especially for calibration and verification purposes.

3.2.1 Dataset and parameters selected for sensitivity analysis

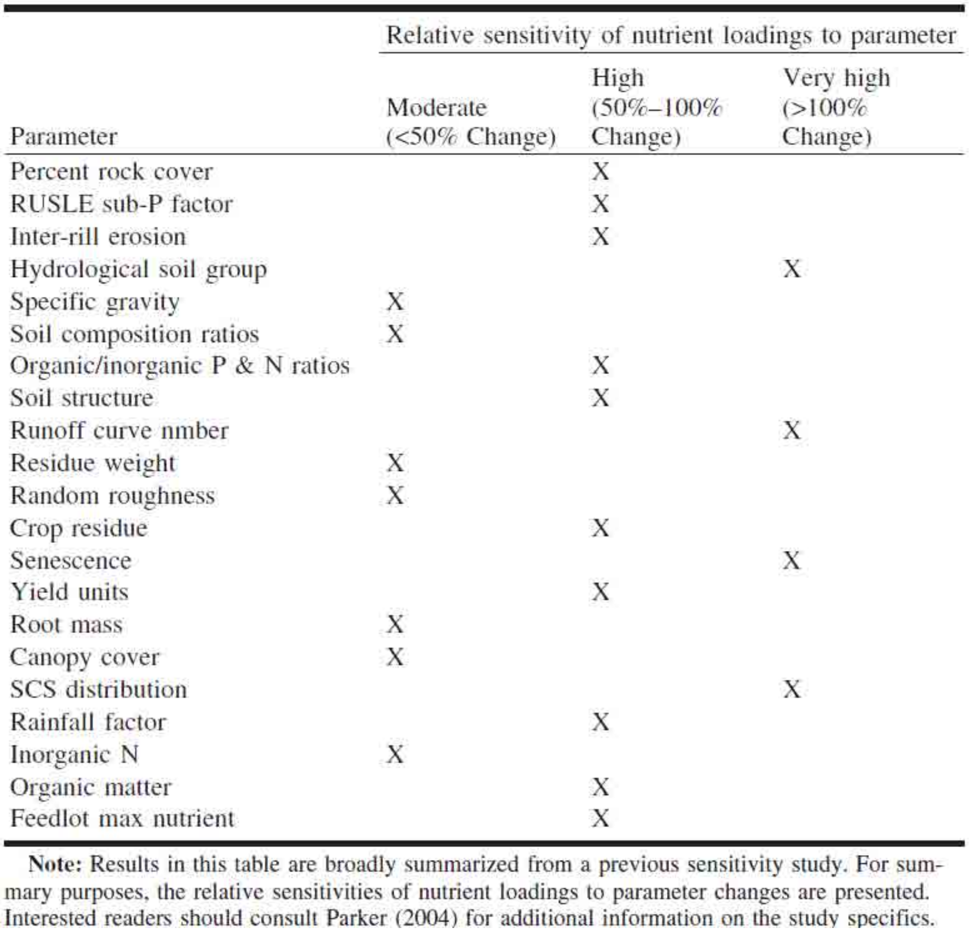
3.2.1.1 Dataset for sensitivity analysis

To demonstrate the performance and capability of the model, the developer provides an input dataset sample that is from the Mission Creek watershed in Oregon, US. This sample not only covers most of the parameters involved in this research but also is quite concise and not time consuming; therefore, it is ideal for sensitivity analysis.

3.2.1.2 Parameters selected for sensitivity analysis

All of the more than 500 input parameters in the model, 33 of which are not used currently but reserved for future model development, are classified into 8 categories and 31 sub-groups. Since this model contains so many parameters, it is not feasible to test each parameter in this research. Also, many studies (Yuan et al., 2003; Das et al., 2008; Liu et al., 2008 and Parker et al., 2008) have already checked the most common sensitive parameters such as crop residue, CN, EI, hydrological soil group, K , P factor, R, soil ratios, yield units and others.

Table 3.1 Summary of sensitivity analysis results (Parker et al., 2008)



	Relative sensitivity of nutrient loadings to parameter		
Parameter	Moderate (<50% Change)	High (50%–100% Change)	Very high (>100% Change)
Percent rock cover		X	
RUSLE sub-P factor		X	
Inter-rill erosion		X	
Hydrological soil group			X
Specific gravity	X		
Soil composition ratios	X		
Organic/inorganic P & N ratios		X	
Soil structure		X	
Runoff curve nmber			X
Residue weight	X		
Random roughness	X		
Crop residue		X	
Senescence			X
Yield units		X	
Root mass	X		
Canopy cover	X		
SCS distribution			X
Rainfall factor		X	
Inorganic N	X		
Organic matter		X	
Feedlot max nutrient		X	

Note: Results in this table are broadly summarized from a previous sensitivity study. For summary purposes, the relative sensitivities of nutrient loadings to parameter changes are presented. Interested readers should consult Parker (2004) for additional information on the study specifics.

To help identify the key parameters which mostly influence the model output, in this research the scope of parameters for sensitivity analysis had been narrowed down to seven parameters that either have not been tested or are very closely related to the objectives of the research shown in Table 3.2.

Table 3.2 Parameters selected for the sensitivity analysis

No.	Parameter	Description and usage	Category
1	Curve number (CN)	Affected by crop types, tillage management, hydrological conditions and etc. used for flow calculation	Runoff curve
2	Fertilizer rate (FR)	Fertilizer application rate, related to N and P exports	Fertilizer application
3	N uptake (NU)	Crop N uptake per yield unit related to N export	Crop
4	Organic matter ratio (OMR)	Ratio of organic matter of total mass of soil in the soil layer, related to N and P exports	Soil
5	P uptake (PU)	Crop P uptake per yield unit related to P export	crop
6	Saturated Hydraulic conductivity (Ksat)	describing water movement through saturated soil, used to calculate flow	Soil
7	TDR	The maximum flow rate per unit area produced from the entire drainage system on a field, used to calculate tile drainage flow	Tile drain

3.2.2 Sensitivity analysis method

The original default values of all parameters in the sample dataset were set to be the base values for the parameters. The model output was calculated with all parameters set to their base values to yield the base output. Each parameter selected for sensitivity analysis was changed by ±25% of its base value to determine its effect on model output; other parameters remained at their base values.

Mathematically, the calculating formula of the sensitivity indicator (SI) can be defined as

$$SI = \frac{(O_b - O_c)/O_b}{(P_b - P_c)/P_b} \qquad \text{Equation 3-9}$$

where

O_b = base output

O_c = output with changed parameter

P_b = base parameter

P_c = changed parameter

Some parameters such as CN, NU, OMR and PU contain many values; therefore, calculating the difference of P_b and P_c, is not possible and Equation 3-9 cannot be applied to these parameters. The simplified formula used for these parameters is

$$SI = \frac{O_c}{O_b} \qquad \text{Equation 3-10}$$

3.2.3 Sensitivity analysis results

For the seven selected parameters taking part in sensitivity analysis, CN, FR, NU, OMR, PU, K_{sat}, and TDR, the SIs are shown as Table 3.3. Sensitivity indices of the various parameters are graphed in Figures 8-15 for their effects on runoff, sediment, and forms of nitrogen and phosphorus.

Table 3.3 SIs of parameters

	Runoff	Sediment	Nitrogen			Phosphorus		
			Attached	Dissolved	Total	Att.Org.	Dis. Inorg.	Total
+25%								
CN	8.586	1.505	1.361	19.852	6.501	1.356	3.454	3.146
FR	1.000	1.000	1.000	1.219	1.061	1.000	1.002	1.001
Ksat	0.996	0.996	0.998	1.002	0.999	0.999	0.985	0.987
NU	1.000	1.000	1.000	0.950	0.986	1.000	1.000	1.000
OMR	1.000	0.959	0.955	0.995	0.966	0.955	1.000	0.994
PU	1.000	1.000	1.000	1.000	1.000	1.000	0.999	1.000
TDR	1.013	0.996	0.997	3.430	1.673	0.997	0.990	0.991
–25%								
CN	0.537	0.431	0.379	0.244	0.341	0.382	0.464	0.452
FR	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Ksat	1.008	0.983	0.984	0.992	0.986	0.984	1.005	1.002
NU	1.000	1.000	1.000	1.051	1.014	1.000	1.000	1.000
OMR	1.000	1.044	1.047	1.007	1.036	1.047	1.000	1.007
PU	1.000	1.000	1.000	1.000	1.000	1.000	1.001	1.001
TDR	1.010	0.997	0.998	2.940	1.538	0.997	0.992	0.993

3.2.3.1 CN

From Table 3.3 and Figures 8-15, the CN parameter is the most sensitive parameter in the model, and it has decisive positive effects on all types of outputs of the model. Specifically, it has a dramatic impact on runoff and dissolved N. Also, according to the experiment, the SI of the CN depends on the value of CN.

3.2.3.2 FR

The FR only affects positively nutrient loadings such as N and P and does not affect runoff and sediment. Dissolved N is more sensitive to this parameter than the other exports.

3.2.3.3 Ksat

From the results of the +25% increment, Ksat has minor positive effects on the dissolved N and minor negative effects on the others, whereas the results from the −25% increment do not always agree with the trends shown by the +25% increment.

3.2.3.4 NU and PU

The NU only has negative effects on all types of N exports; the other exports such as runoff, sediment and phosphorus are not affected. In comparison to attached N, dissolved N appears more sensitive to NU. Like NU, PU only has a negative influence on P related exports. The difference is that the attached inorganic P is not affected by the PU. Generally, nutrient exports of the model decrease with crop uptake increase.

3.2.3.5 OMR

The OMR is connected with all exports but runoff having negative effects on sediment, nitrogen, and phosphorus.

3.2.3.6 TDR

All sorts of outputs of the model have relationships with the TDR parameter. Especially dissolved N is very sensitive to the TDR. As a result, the total N is also considerately sensitive to the TDR.

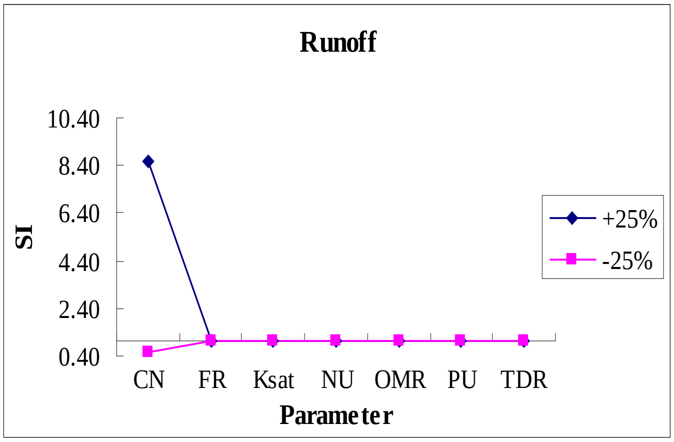


Figure 8 Effects on runoff

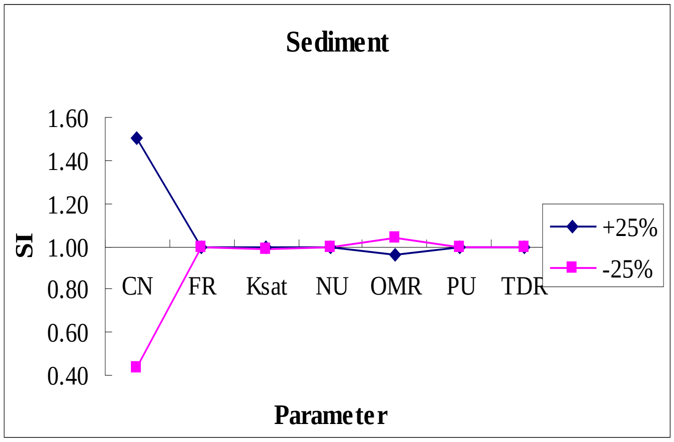


Figure 9 Effects on sediment

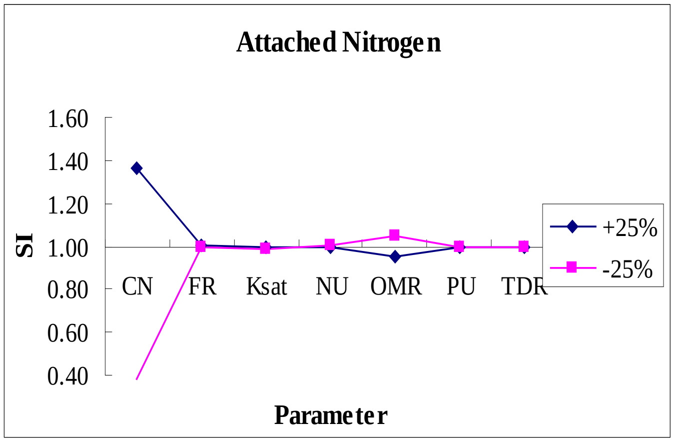


Figure 10 Effects on attached N

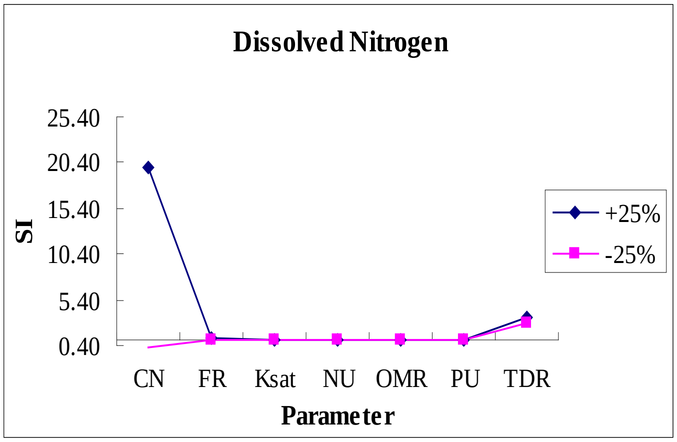


Figure 11 Effects on dissolved N

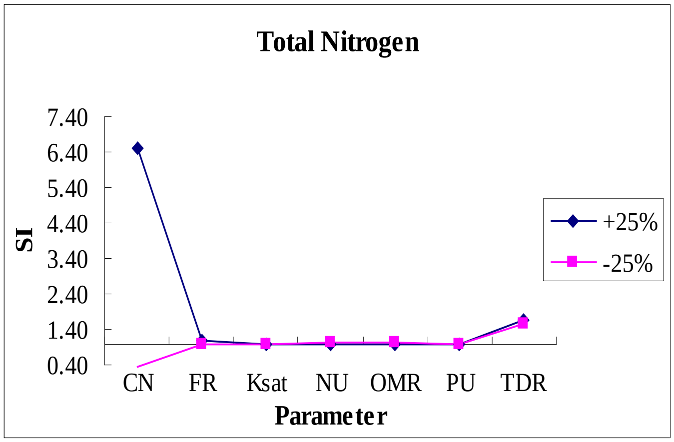


Figure 12 Effects on total N

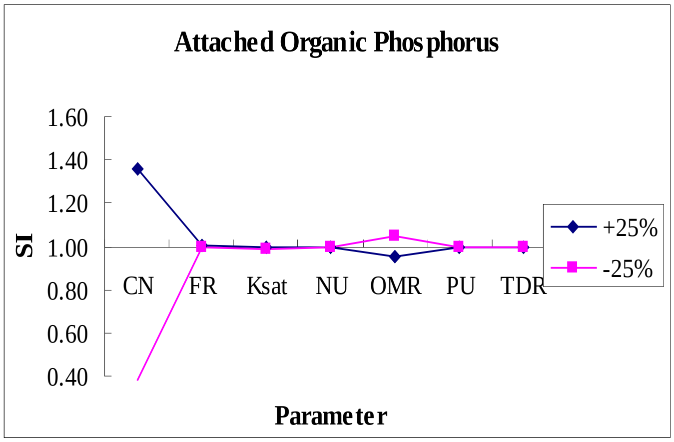


Figure 13 Effects on attached organic P

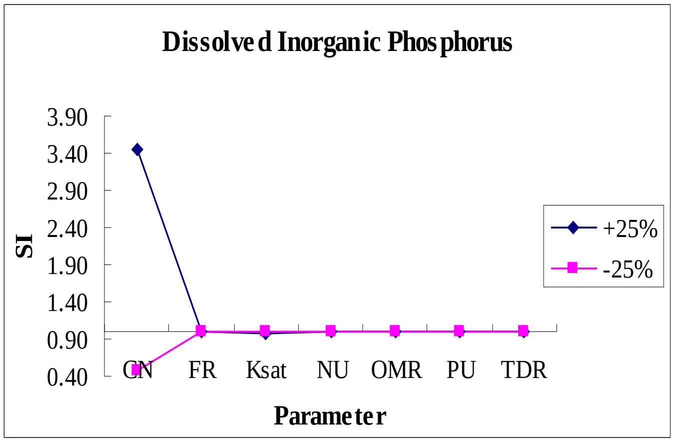


Figure 14 Effects dissolved inorganic P

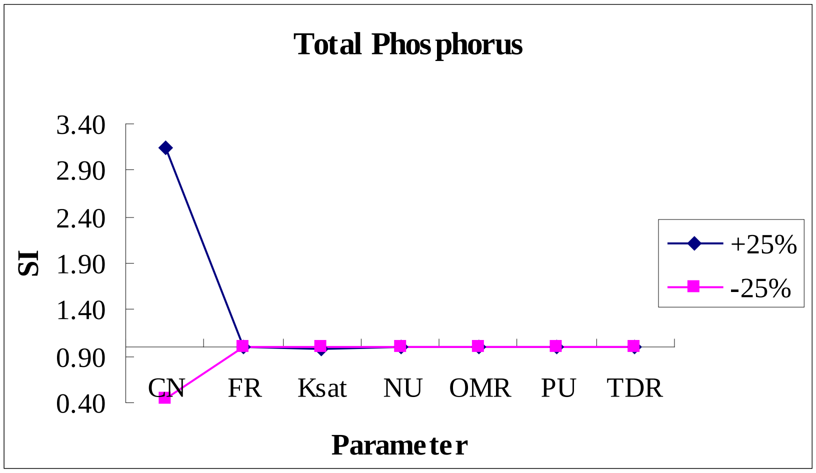


Figure 15 Effects on total P

3.2.4 Summary

From the above analysis, the CN is the most sensitive and important parameter in the model as Bosch et al. (1998) found; CN has the most influence on runoff and other outputs of the model. This outcome can be reasonably explained by the technique of calculating surface flow that employs the SCS CN method; therefore, to set up a qualified model for a watershed, it is of extreme importance to choose a set of matching CNs for the watershed. Other nutrients related parameters such as FR, NU and PU only have influence on nutrient exports. Consequently, they play an important role in calibrating and verifying nutrient exports. The soil parameter, Ksat, affects all exports according to the results. Compared to the other soil parameter OMR, it behaves in a quite different way. It shows moderate influence on sediment and N exports. Simultaneously, it is also richly varied and difficult to be measured within a watershed, especially for a large watershed with a variety of soil types.

The TDR has the capability of regulating all exports of the model, particularly for dissolved N. This inspires the creative idea that the tile drainage BMP through designing tile drainage scenarios will be an important factor in mitigating the export of this nutrient to receiving waters. This parameter is the key for designing TDR scenarios and TDR calculations based on experimental data from the WEBs project.

CHAPTER 4

MATERIALS AND METHODOLOGY

The AnnAGNPS input file consists of 38 sections of data that are capable of dealing with more than 500 types of parameters. To prepare and manage this large number of parameters in an effective way is a challenging task, and they are mainly discussed in this chapter. The main input file layout is given in Appendix E.

4.1 Climate Data

Climate is the major role and driver in the hydrologic cycle. The climate data contain daily climate data separated from the other specific watershed data and arranged in an independent file normally named DayClim.inp, which is composed of maximum temperature, minimum temperature, precipitation, dew point, sky cover and wind speed.

4.1.1 Climate data source and potential weather gauging stations

Due to the limit of use within the US of the weather generator provided by the model and to achieve the best representation of the reality of the watershed, this research used historical climatic records acquired from the online database of the National Climate Data and Information Archive (EC, 2008). The period was from 1971 to 2008. A program was created to reformat climate data (detailed in Appendix D.1)

In order to present precisely the climate of the watershed, this research demanded as many weather gauging stations as possible. At first there were 44 potential weather stations neighbouring the watershed as shown in Figure 16; however, many of them do not have an integrated observation series from 1971~2008.

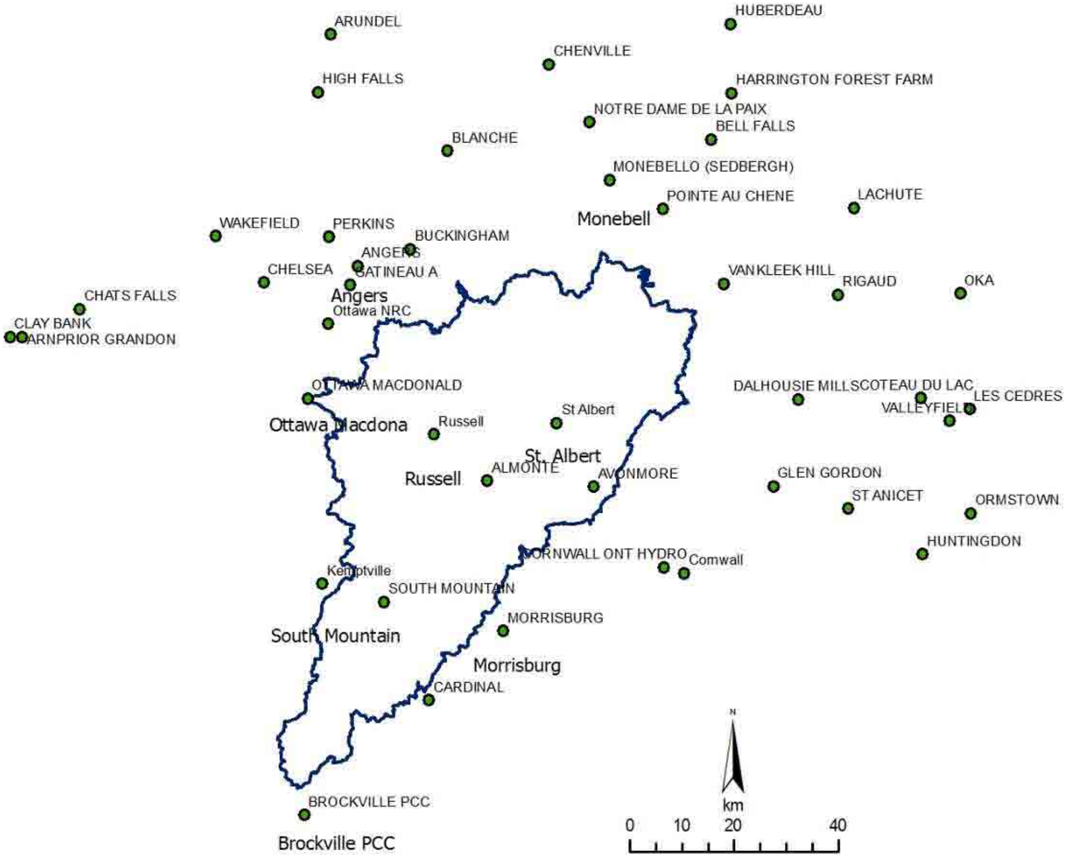


Figure 16 Potential weather stations neighbouring the watershed

4.1.2 Chosen weather gauging stations and Thiessen polygon

After comprehensive comparison of results using various stations, 8 stations were considered to be capable of representing the watershed. On the basis of these 8 stations, a Thiessen polygon as shown in Figure 17 was generated for the AnnAGNPS model. Afterwards, it would be intersected with the sub-watershed shape file in ArcView and transfer weather station IDs to each cell. Accordingly, the model can obtain proper climate data for each cell through station IDs.

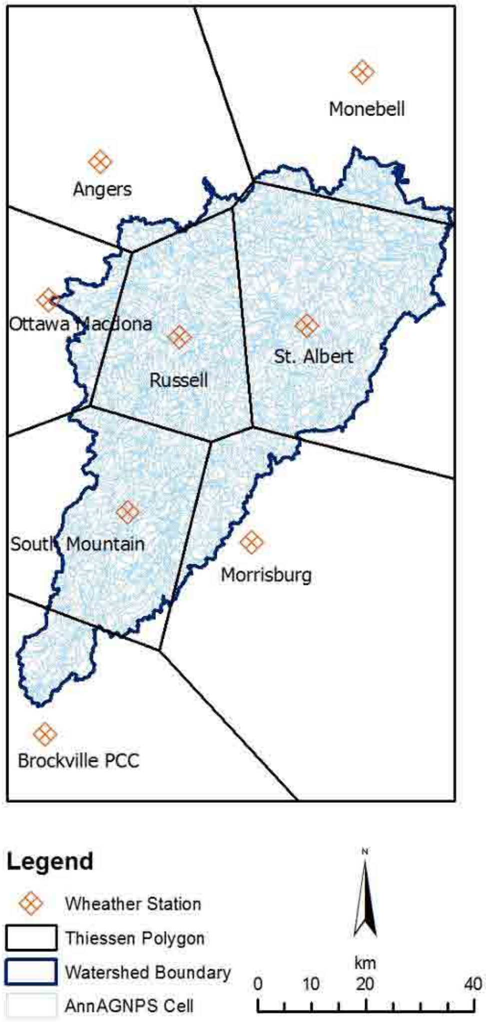


Figure 17 Weather stations used in modelling and corresponding Thiessen polygons

4.2 Crop Data

4.2.1 Types of corps and crop rotation

Based on a survey by Pommainville (2007), cereals, corn, grass hay and soybean are the main crops grown within the watershed. For cropland without hay planting, crop rotation is considered to be three years in the sequence: cereals-corn-soybean. Cropland with hay planting has a six year cycle: cereals-corn-soybean, and the following three years are in hay.

4.2.2 N and P uptake

In light of above sensitivity analysis, N and P uptakes of crop are related to the nutrient exports of the model. The ratio of 0.022 was assigned to cereal N uptake, and 0.0025 to cereal P uptake; the ratios of 0.092 and 0.0095 were given to soybean N and P uptake, respectively (Yuan et al., 2003). According to the reference data provided by the model package and suggestions from experts at AAFC, corn N and P uptakes were set at 0.016 and 0.0055, respectively; hay N and P uptakes were set to 0.0225 and 0.00425, respectively.

4.3 Fertilizer Data

According to observed data from the WEBs project and a survey on agricultural management practices in the SNW, chemical fertilizer application rate shown in Table 4.1 varies according to the type of crop grown. Manure spreading is normally done in either late summer or early fall to prepare for corn planting next year. The application rate of liquid manure is 56000 kg/ha.

Table 4.1 Chemical fertilizer application

No.	Crops	Fertilizer application (kg/ha)	Fertilizer brand
1	Corn	150	10-34-0
2	Cereals	120	10-34-0
3	Soybean	160	Super P
4	Hay	80	10-10-10

4.4 Land Use Data

4.4.1 Land use intersection and distortion error

The model is limited to defining six types of acceptable land use: cropland, pasture, rangeland, forest, urban and water. Land use spatial/temporal data on agricultural practices were acquired from the Eastern Ontario Water Resources Management Study (EOWRMS) (CH2MHILL, 2001) (detailed in Appendix B). Figure 18 shows the comparison between the land use input into the model and the results from the EOWRMS study.

The differences in the land use in the model input and the EOWRMS study are mainly due to some limitations in the AnnAGNPS model discussed below. The errors between the two are described in Table 4.2.

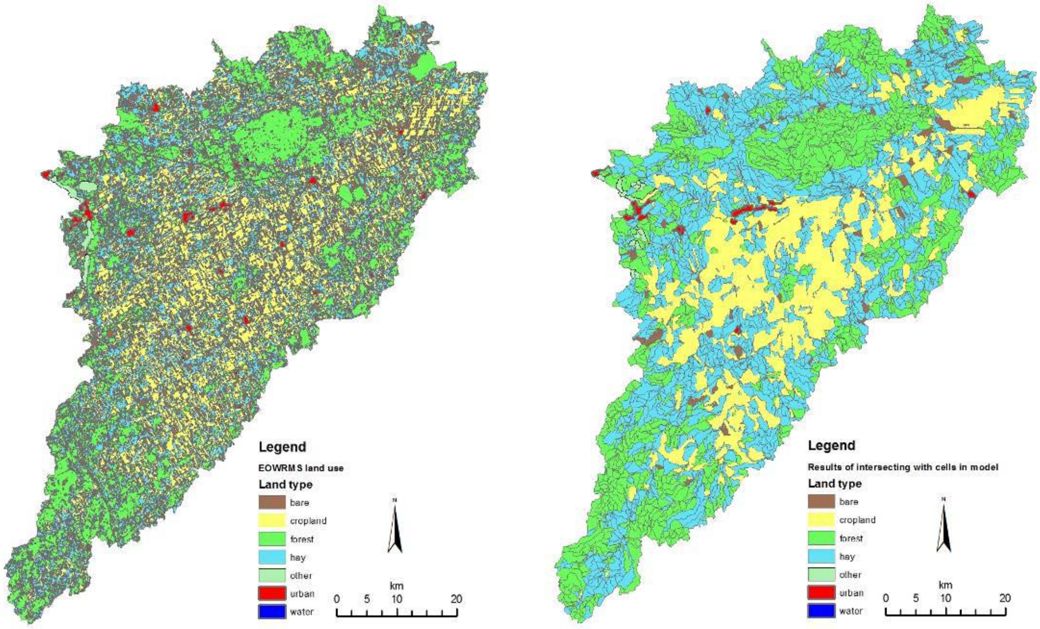


Figure 18 Comparison of land use by EOWRMS and Results of intersection in model

Table 4.2 Errors on intersecting distortion

Land use	**Area from EOWRMS (m^2)**	**Area of intersection (m^2)**	**Relative error**	**Total error**
bare	3.87×10^{8}	6.29×10^{7}	0.84	0.0857
cropland	8.54×10^{8}	8.47×10^{8}	0.01	0.0019
forest	1.12×10^{9}	1.20×10^{9}	0.07	0.0220
hay	1.36×10^{9}	1.63×10^{9}	0.20	0.0707
other	1.74×10^{7}	1.60×10^{7}	0.08	0.0004
urban	3.40×10^{7}	2.21×10^{7}	0.35	0.0031
water	6.40×10^{6}	3.88×10^{5}	0.94	0.0016
Sum	3.78×10^{9}	378×10^{9}		0.1853

Theoretically, the total error is inversely proportional to the number of cells. As the watershed is delineated into more cells, a lower total error can be achieved, and a more accurate model can be obtained. In this research, intersection errors are shown in Table 4.2. Unfortunately, the current software and hardware conditions limit the capability of processing a greater number of cells. This restriction will be discussed in the topographic data section.

4.4.2 Redefinition of land use for the model

EOWRMS defined seven types of land use: bare, cropland, forest, hay, other, urban and water, whereas the model only accepts six types of land uses as prescribed above. Thus, some sorts of land uses in the EOWRMS map have to be redefined considering the actual situation in the watershed in the model. The redefinitions are given in Table 4.3.

Table 4.3 Redefinition of land use

No.	**Land use by EOWRMS**	**Land use redefined in model**
1	Cropland, hay,	Cropland
2	Forest	Forest
3	Bare, other	Pasture
4	Urban	Urban
5	Water	Water

4.5 Management Data

Management data consist of many important parameters included in management field, management schedule and management operation sections, related to all types of exports of the model such as field management schedule and field operation. Management data are also the interface to carry out BMP scenarios.

4.5.1 Management field

The management field mainly contains important parameters such as field land use type, management schedule ID, tile drain ID and other field management information. Land use type can be assigned through intersection with land use dataset discussed in land use data section in ArcView. The schedule and tile drain IDs inform the model field schedule in Section 4.5.2 and TDR scenario in Section 6.2.

4.5.2 Management schedule

The schedule of the management of the crop rotation without hay planting will only go through the first three years defined in Table 4.4, and the schedule for the crop rotation with hay planting will follow the three year sequence defined in the table followed by the three year schedule for cereals, corn and soybean.

Table 4.4 Schedule of the crop rotation with hay planting

Year	Date	Crop	Fertilizer (kg/ha)	Field operation
1	Apr. 22	Cereals	50	Plant
	May 20			Weed spray
	Jun. 15		70	
	Aug. 25			Harvest
	Aug. 30			Harrow
	Sept. 2		56000 (Liquid manure)	
2	May 10	Corn	60	Plant
	Jun. 20			Weed spray
	Jun. 25		90	
	Oct. 15			Harvest
	Oct. 20			Harrow
3	May 20	Soybean	160 (Super P)	Plant
	Jun. 25			Weed spray
	Sept. 15			Harvest
	Sept. 20			Harrow
4	Apr. 25	Hay	80	Plant
	Sept. 25			Harvest
	Sept. 30			Harrow
5	Apr. 25	Hay	80	Plant
	Sept. 25			Harvest
	Sept. 30			Harrow
6	Apr. 25	Hay	80	Plant
	Sept. 25			Harvest
	Sept. 30			Harrow

4.5.3 Management operation

Field changes such as soil surface disturbed, planting crop, harvest, current crop killed, etc. are described as management operations in the model, and they are defined as:

1. No effect

2. Soil surface disturbed

3. Current crop residue added to surface

6. Current crop harvested

7. Plant crop (growth begins)

8. Current crop killed

Table 4.5 Management operation definition

No.	**Operation ID**	**Effect codes**				
1	Plant	2	7	1	1	1
2	Weed spray	1	1	1	1	1
3	Fertilizer	2	1	1	1	1
4	Harvest	6	3	8	1	1
5	Harrow	2	1	1	1	1
6	Hay plant	2	1	1	1	1

4.6 Runoff Curve Number Data

It is difficult to define proper CNs for a watershed like the SNW with diverse situations. To solve this problem, the model provides a reference CN sheet which contains recommended CNs for varieties of land covers, vegetations, etc. Based on vegetation and land covers in the watershed, 8 sets of runoff CNs are defined in the research as given in Table 4.6.

Table 4.6 Runoff curve number defined in the model

Curve number ID	**Soil hydrologic group**			
	A	**B**	**C**	**D**
Brush_Weed_Grass_RCN	35	56	70	77
Fallow_Poor_Yes	74	83	88	90
Small_Grain_Straight_Row_Poor	60	72	80	83
Row_Crops_RCN	64	74	81	85
Close_Seeded_Legume_Poor_RCN	55	69	78	83
Woods_RCN	36	60	73	79
Pasture_RCN	49	69	79	84
Urban_RCN	77	85	90	92

4.7 Soil Data

Soil data were obtained from Canadian Soil Information System (AC, 2007) (detailed in Appendix C); the GIS soil coverage in this database has a resolution of 90 m. this soil database contains plenty of soil information for related soil parameters such as hydrologic soil group, soil layer, ratios of clay, silt and sand, K_{sat}, organic matter ratios, etc. For this model, these parameters all can acquire reliable values from the soil database.

There are 70 types of soil in the model defined in the soil database within the watershed with up to six layers for 248 in total after intersection with the soil GIS shape file. An average value of 0.0455 for the watershed was used for the RUSLE K factor (Schut et al., 1987). The comparison of the original soil data from Canadian Soil Information System with the results of soil data input data in the model is shown in Figure 19.

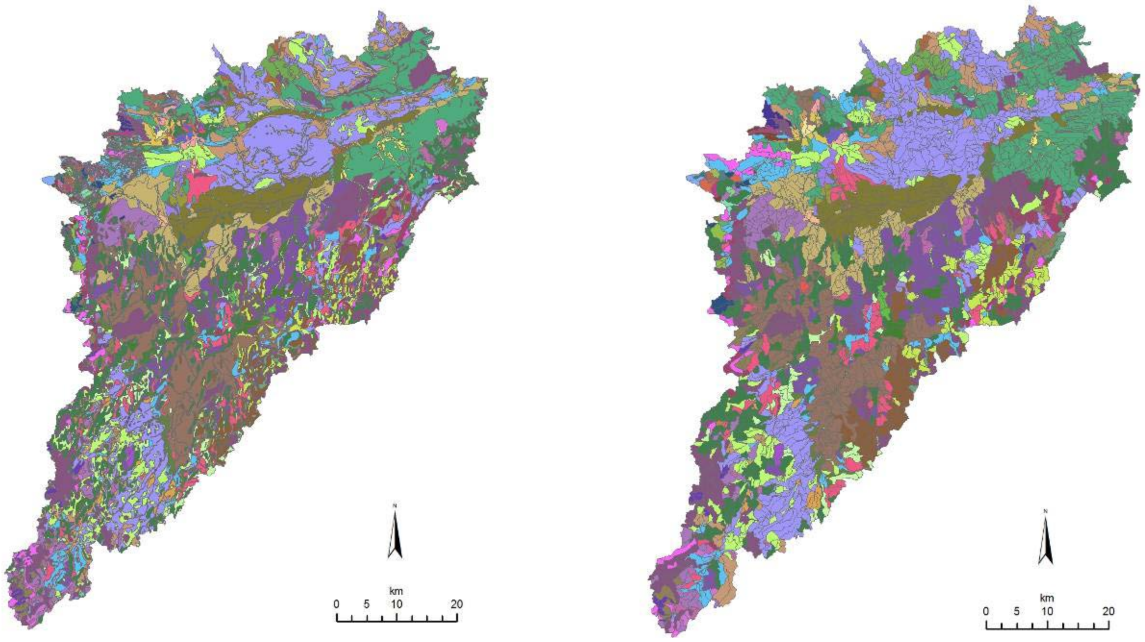


Figure 19 Comparison of the original soil with the result of intersection

4.8 Tile Drainage Data

As described in Section 1.1, the SNW is rather flat with an average slope of approximately 0.05% from the source to its exit to the Ottawa River at Plantagenet. This type of terrain is suitable for building tile drainage systems. As targeted in Section 1.3, the research objective is to evaluate CTD effects on surface water quality; therefore, the calculation of the tile drainage data is critical to this research. The tile drainage data are specifically described in Chapter 6.

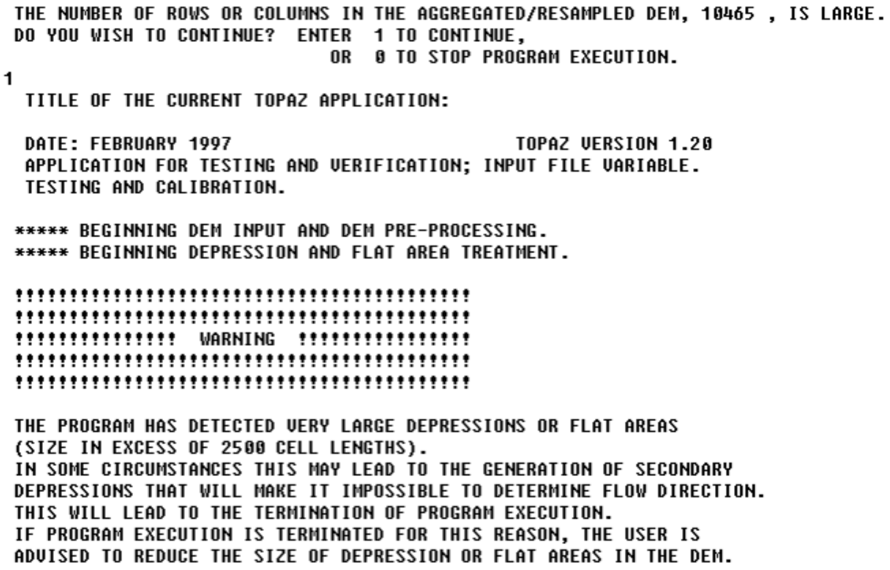
4.9 Topographic Data

The digital elevation model (DEM) for the watershed was generated using the Ontario Ministry of Natural Resources (OMNR) database (detailed in Appendix A), and its resolution was changed to 30 m from 10 m because of limitations of TOPAZ which is the pre-processor used by AnnAGNPS to define the cells, reaches and other topographic characteristics such as area, elevation slope, and length in cells. TOPAZ retrieves useful topographic information from the DEM, and then another processing module called Agflow translates the information into usable format for the model.

4.9.1 CSA, MSCL and Limitation of the Model

The number of cells and reaches of the model were determined by two most important hydrologic parameters for DEM processing, critical source area (CSA) and minimum source channel length (MSCL). Consequently, the topology and characteristics of the cells and reaches generated by TOPAZ are all affected by these two parameters.

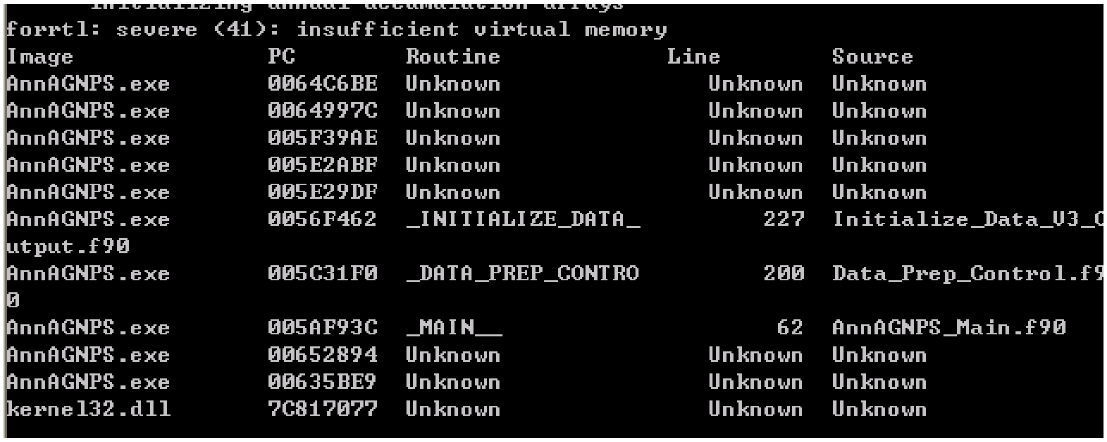
Theoretically, more cells and reaches can provide more detail on the watershed; thereby the model has a solid basis to reflect the reality of a watershed. However, the current hardware and software conditions put restrictions on the number of cells and reaches.



```
 THE NUMBER OF ROWS OR COLUMNS IN THE AGGREGATED/RESAMPLED DEM, 10465 , IS LARGE.
 DO YOU WISH TO CONTINUE?  ENTER  1 TO CONTINUE,
                              OR  0 TO STOP PROGRAM EXECUTION.
1
  TITLE OF THE CURRENT TOPAZ APPLICATION:

  DATE: FEBRUARY 1997                          TOPAZ VERSION 1.20
  APPLICATION FOR TESTING AND VERIFICATION; INPUT FILE VARIABLE.
  TESTING AND CALIBRATION.

 ***** BEGINNING DEM INPUT AND DEM PRE-PROCESSING.
 ***** BEGINNING DEPRESSION AND FLAT AREA TREATMENT.

 !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
 !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
 !!!!!!!!!!!!!!!  WARNING  !!!!!!!!!!!!!!!!
 !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
 !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

 THE PROGRAM HAS DETECTED VERY LARGE DEPRESSIONS OR FLAT AREAS
 (SIZE IN EXCESS OF 2500 CELL LENGTHS).
 IN SOME CIRCUMSTANCES THIS MAY LEAD TO THE GENERATION OF SECONDARY
 DEPRESSIONS THAT WILL MAKE IT IMPOSSIBLE TO DETERMINE FLOW DIRECTION.
 THIS WILL LEAD TO THE TERMINATION OF PROGRAM EXECUTION.
 IF PROGRAM EXECUTION IS TERMINATED FOR THIS REASON, THE USER IS
 ADVISED TO REDUCE THE SIZE OF DEPRESSION OR FLAT AREAS IN THE DEM.
```

Figure 20 Error caused by TOPAZ

There are two types of errors caused by these restraints, one is generated by TOPAZ as shown in Figure 20, and the other is from the main program of the model shown in Figure 21. They are all caused by the memory capacity and the addressing capability of the operating system.



```
      Initializing annual accumulation arrays
forrtl: severe (41): insufficient virtual memory
Image              PC        Routine            Line        Source
AnnAGNPS.exe       0064C6BE  Unknown               Unknown  Unknown
AnnAGNPS.exe       0064997C  Unknown               Unknown  Unknown
AnnAGNPS.exe       005F39AE  Unknown               Unknown  Unknown
AnnAGNPS.exe       005E2ABF  Unknown               Unknown  Unknown
AnnAGNPS.exe       005E29DF  Unknown               Unknown  Unknown
AnnAGNPS.exe       0056F462  _INITIALIZE_DATA_         227  Initialize_Data_V3_O
utput.f90
AnnAGNPS.exe       005C31F0  _DATA_PREP_CONTRO         200  Data_Prep_Control.f9
0
AnnAGNPS.exe       005AF93C  _MAIN__                    62  AnnAGNPS_Main.f90
AnnAGNPS.exe       00652894  Unknown               Unknown  Unknown
AnnAGNPS.exe       00635BE9  Unknown               Unknown  Unknown
kernel32.dll       7C817077  Unknown               Unknown  Unknown
```

Figure 21 Error caused by the main program

These errors ultimately relate to the 32 bit memory limitation of Windows. The first error is that TOPAZ cannot handle a DEM with more than 2000 by 4000 rows and columns which the DEM of the SNW at 10 m resolution yields. To solve this issue, the strategy is to resample the DEM to 30 m. The second error is that the numbers of cells exceeds the capability of the model resulting from the memory limit of a 32 bit operating system. The strategy is to reduce the number of cells by way of defining a set of proper CSAs and MSCLs as discussed in the next section. Also, the computation time increases exponentially as the numbers of cells and reaches grows.

4.9.2 Cells and Reaches

As discussed in Section 4.9.1, the model is restricted from both physical and software conditions of the computer and computing time. Therefore based on efficiency and capability of the model, CSA was set to 90 ha, and MSCL was set to 900 m. The pair of values assures that the number of cells generated by the model is very close to but not beyond the limit of the model based on current computer conditions, and the delineation result can well represent the characteristics of the watershed. The whole watershed was delineated into 3629 effective cells with 1456 reaches shown in Figure 22.

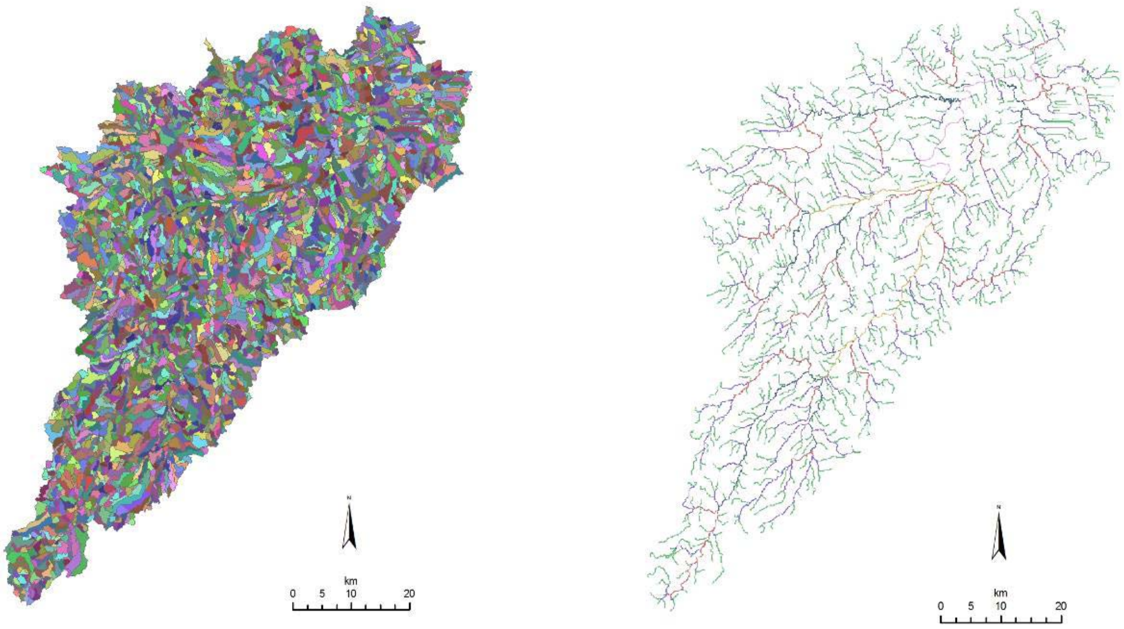


Figure 22 Cells and reaches generated in the model

CHAPTER 5

CALIBRATION AND VALIDATION

In order to match field conditions and the observations within some acceptable criteria, it is necessary to calibrate the simulation results with the corresponding observations by modifying related input parameters. Then validation can ensure that the model accurately represents the reality of the watershed by comparing the revised model to the reality of the watershed.

5.1 Observed data, Periods and criteria

5.1.1 Observed Data

5.1.1.1 Runoff and Sediment

Runoff and sediment data used for calibration and validation were taken from Archived Hydrometric Data maintained by Water Survey of Canada at the Plantagenet gauging station (EC, 2008). The model only simulates direct runoff rather than discharge, thus runoff needs to be separated from base flow. The separation of runoff from discharge was completed by Web based Hydrograph Analysis Tool (WHAT) system (Lim et al., 2005).

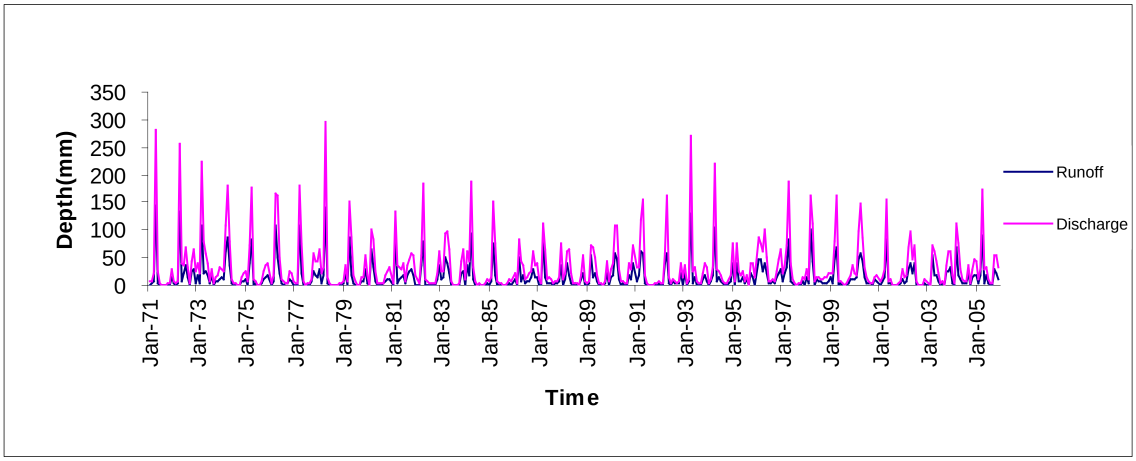


Figure 23 Monthly observed discharge and runoff separated by WHAT (1971 ~2005)

Based on discharge observations from 1971 to 2005 at Plantagenet, the annual average discharge is 153×10^7 m^3, and the annual average runoff is 68.9×10^7 m^3 using WHAT. The monthly results are shown in Figure 23.

In comparison to discharge data at the Plantagenet gauging station, sediment data are relatively few and deficient. There are only a few years of sediment data available, from 1972 to 1983 and 1993 as shown in Figure 24.

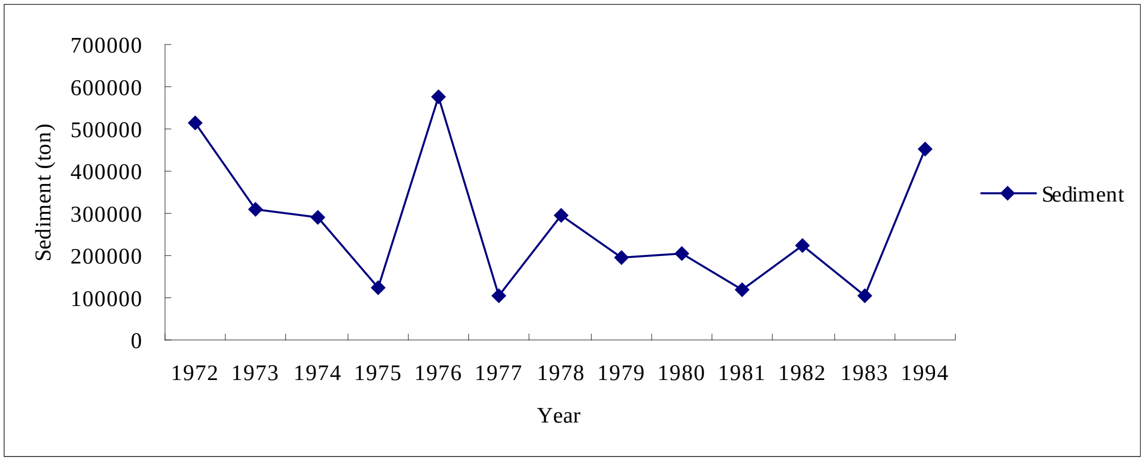


Figure 24 Observed sediment data at Plantagenet gauging station

5.1.1.2 Nitrogen and Phosphorus

Observed nitrogen and phosphorus data were taken from the Provincial Water Quality Monitoring Network (PWQMN) at the Plantagenet gauging station, which collects surface water quality information such as chloride, nitrogen, phosphorus, suspended solids, metals and other general chemistry parameters from rivers within Ontario. The data from PWQMN provides ample breakdown of nitrogen and phosphorus chemical forms. For instance, nitrate, nitrite and ammonia are reported forms for nitrogen. Since Ann AGNPS can only simulate two forms of nutrients, the attached and the dissolved forms, the observed data related to N and P have to be generalized into total N and total P, respectively, used for calibrating the nutrient part of the model.

5.1.2 Periods

According to the availability and integrity of the observed data at Plantagenet, The calibration years for flow, nutrients and sediment were 1973-77, 1971-73 and 1973-81, respectively; the validation years were 1980-81, 1974-77 and 1983-93, respectively.

5.1.3 Criteria

For each parameter and both periods, the quality of the fit was evaluated using visual inspection of modelled vs. observed results and three performance criteria: the Nash coefficient of efficiency E (Nash et al., 1970), the root mean square error (RMSE) and the coefficient of residual mass (CRM) (Loague et al., 1991) defined in Table 5.1.

Table 5.1 Statistical performance criteria

Criteria	**E**	**RMSE**	**CRM**
Formula	$E = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2}$	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$	$CRM = \frac{\sum_{i=1}^{n}O_i - \sum_{i=1}^{n}P_i}{\sum_{i=1}^{n}O_i}$
Range	$(-\infty,1]$	$[0,+\infty)$	$(\infty,+\infty)$

Where O is observed data, correspondingly P is simulated data (predicted value), $\overline{O}$ and $\overline{P}$ are separately the means of observed and simulated series, i is the sequence number of an event and n is the total number of events in the series.

5.2 Calibration and Validation

Based on transportation mechanisms among runoff, sediment, N and P the yield of sediment is related to runoff and runoff and sediment influence N and P. Therefore the sequence of calibration should be runoff, sediment, N and P.

5.2.1 Runoff

Performance parameters were calculated using monthly observed and simulated values. Calibration involved adjusting many parameters such as CN, rainfall, and soil within a reasonable range. Initial values of CN were estimated from land use and soil data. These values were further modified in the calibration process to improve the match of observed and simulated runoff volumes. The final results of the calibration are shown in Figure 25.

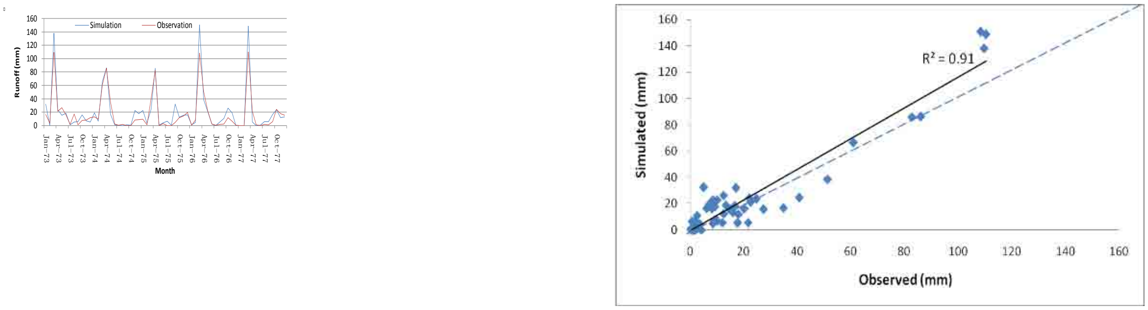


Figure 25 Comparison of observed and simulated runoff (calibration)

The monthly simulated results from Jan. 1980 to Dec. 1981 were validated as shown as Figure 26.

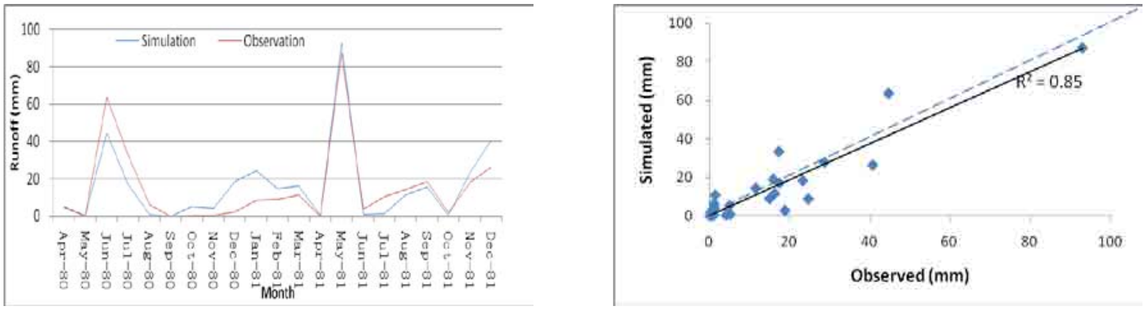


Figure 26 Comparison of observed and simulated runoff (validation)

From Figures 25 and 26, it can be seen that there is an excellent match between the simulated and observed values in both calibration and validation phases. Strong fits are also shown by the values of the criteria in Table 5.2.

5.2.2 Sediment

Due to the shortage and the poor quality of observed sediment data, performance measures were calculated using yearly observed and simulated values. Observed and simulated values for the calibration and validation are shown in Figures 27 and 28, respectively. Performance measures are presented in Table 5.2 given below. The value of the Nash coefficient E is higher than usually obtained for sediment data. But the observed and predicted curves for the validation years show significant disagreement due to the small amount of available sediment data. For all available data the results were acceptable and no further improvements could be obtained by adjusting model parameters.

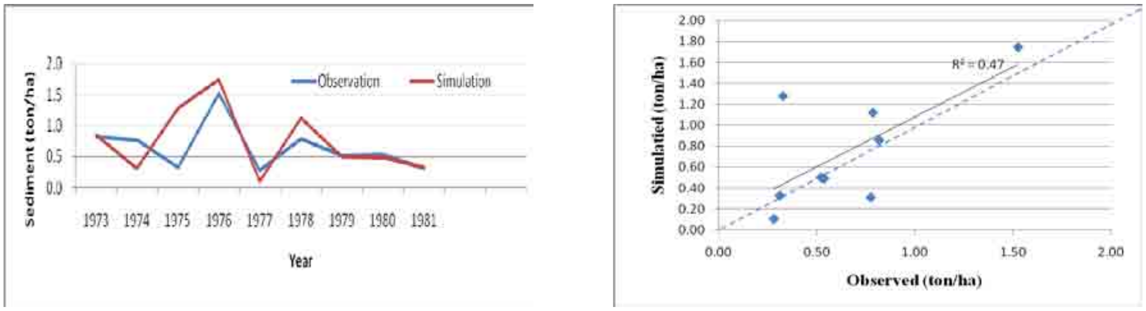


Figure 27 Comparison of observed and simulated sediment (calibration)

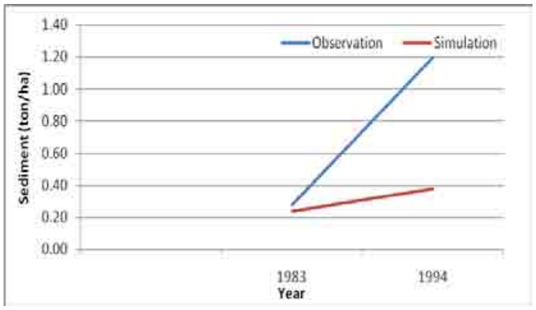


Figure 28 Comparison of observed and simulated sediment (validation)

5.2.3 Nitrogen

N was calibrated by adjusting crops N uptake along with organic and inorganic N ratio. Compared to the R-square value of 0.28 obtained by Yuan et al. (2003), performance measures for both the calibration and validation phase indicate that the model performs very well for N simulation. Results are shown in Figures 29 and 30.

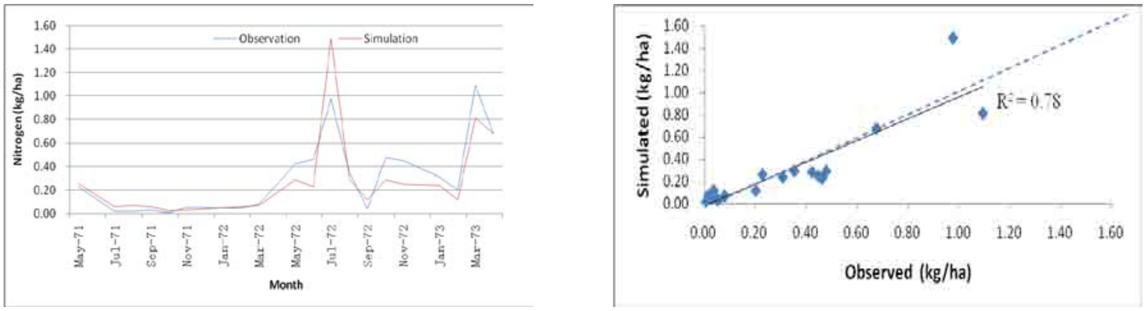


Figure 29 Comparison of observed and simulated N (calibration)

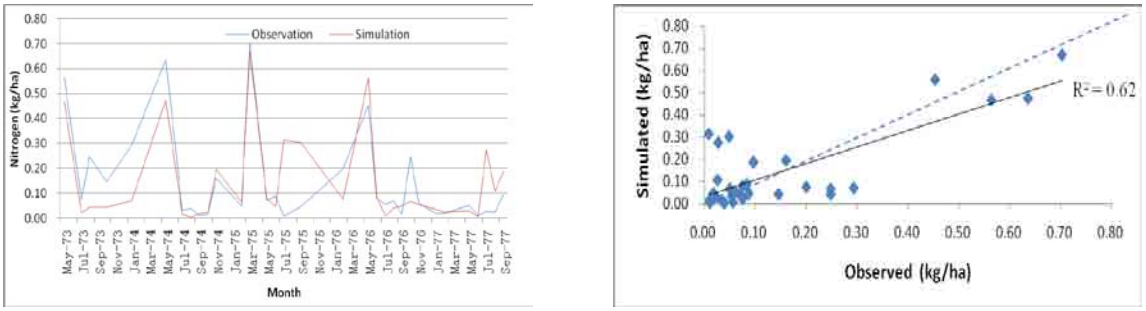


Figure 30 Comparison of observed and simulated N (validation)

5.2.4 Phosphorus

Similar to N, P was also calibrated by adjusting P uptake of crops, ratios of organic P and inorganic P. Simulation results are presented in Figures 31 and 32.

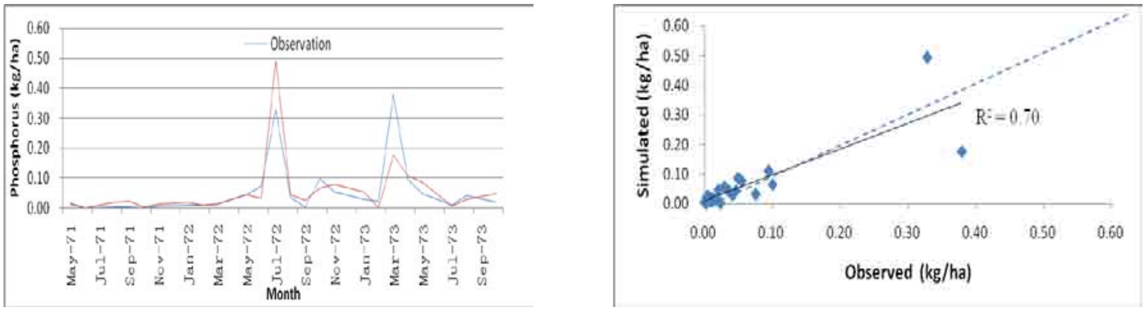


Figure 31 Comparison of observed and simulated P (calibration)

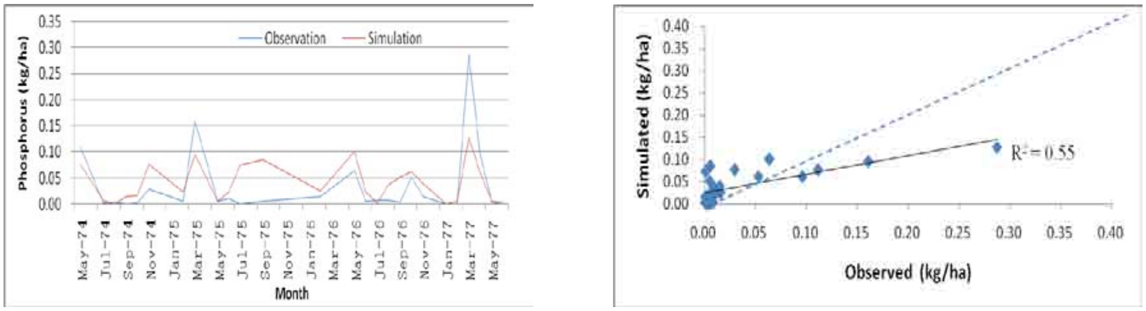


Figure 32 Comparison of observed and simulated P (validation)

According to the formulas in the Table 5.1, results of statistical performance criteria are given in Table 5.2.

Table 5.2 Statistical results for all simulated parameters

Parameter	***E***	***RMSE***	***CRM***
Runoff			
Calibration	0.83	8.08	□0.16
Validation	0.85	3.68	□0.05
Sediment			
Calibration	0.74	0.06	□0.15
Validation	0.55	0.10	0.59
Nitrogen			
Calibration	0.73	0.09	0.09
Validation	0.60	0.09	0.04
Phosphorus			
Calibration	0.64	0.04	–0.05
Validation	0.51	0.03	–0.15

5.2.5 Summary

The extensive calibration and validation exercises of the model based on observations of discharge, sediment, N and P in the SNW yielded statistical indices on four types of exports of the model, runoff, sediment, N and P, which are well above typical values found in the literature (Yuan et al., 2001, .Polyakov et al., 2007, Das et al. 2008).

The model performed very well on simulating runoff, sediment and N for the conditions of the watershed. Although the E of phosphorus is an acceptable value for simulations of the P nutrient, the performance of the AnnAGNPS on simulating P process shows deficiencies as Yuan et al. (2005) noted. They found that AnnAGNPS is not capable of simulating dissolved P on a monthly basis due to the complexities of all the forms and processes involved in the phosphorous cycle in nature.

Overall, based on the calibration and validation, the performance of the model applied in the South Nation River basin on predicting runoff, sediment and N is considered satisfactory, and the model can be used to evaluate the impacts of CTD scenarios or other scenarios on surface water quality in the watershed.

CHAPTER 6

TILE DRAINAGE RATE AND SCENARIOS DESIGN

6.1 Tile Drainage BMP

Agricultural BMPs are accepted as the most effective techniques designed to prevent or reduce pollutants from agricultural areas as well as enhance agricultural production. In practice, many techniques such as nutrient application rates, vegetative filter strips, tillage reduction, livestock access control to water bodies, tile drainage and others have been proven to be effective BMPs for agriculture. Compared to other BMPs on an historical basis, tile drainage has been widely applied in agriculture due to its simplicity and effectiveness.

Nowadays, this technique is still broadly used in agriculture. Furthermore, a large number of advances in tile drainage such as installation method, material replacement, and operation mode have been made to adapt this ancient technique to modern conditions.

6.1.1 Uncontrolled Tile Drainage

Conventional tile drainage (UCTD) runs without manual intervention. Once it is installed in a field, it will function automatically and only be restricted by .natural conditions such as tile diameter, spacing, depth and other physical conditions.

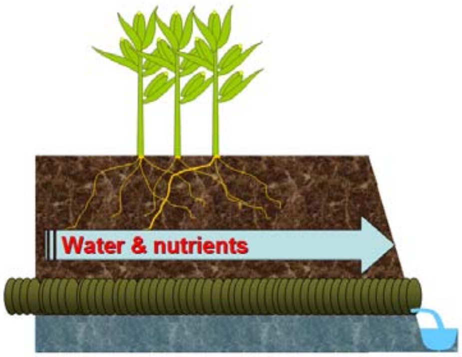


Figure 33 Schematic of UCTD

6.1.2 Controlled Tile Drainage

Inversely, CTD is operated manually through a controllable facility based on concrete needs in specific conditions. It restricts outflow from tile drained crop fields, thereby elevating the water table and maintaining nutrient laden water in contact with crop root zones which is expected to not only increase yields but also significantly decrease pollutant discharges.

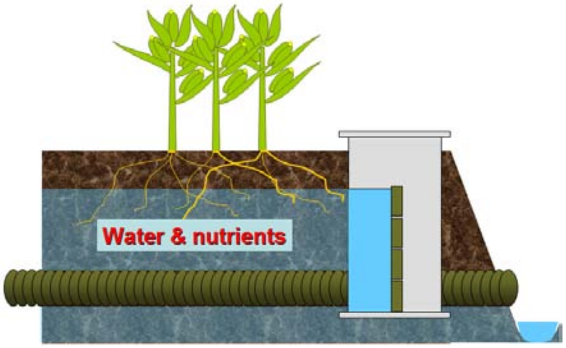


Figure 34 Schematic of CTD

6.1.3 Comparison of CTD and UCTD

UCTD allows water and nutrients to flow directly from the tiled field to ditches or streams; whereas CTD restrains flow and nutrients inside the tiled field during the growing season. Both techniques are known to be capable of increasing crop yields; however, CTD due to its controllable nature is more adaptable to specific conditions. As a result CTD is expected to cause a greater increase in the yields and significantly decrease pollution release to neighbouring streams.

6.2 TDR Scenarios design

6.2.1 CTD, UCTD and TDR

In a CTD area, tile drainage will be controlled by installing small dam structures with water overflow systems at header drain outlets shown in Figure 35 to seasonally restrict the water in these drains from discharging into canals, thereby retaining soil water and nutrients in the field for crop growth. The tile drain spacing is 15 m buried underground 0.8m, and the pipe shown in Figure 36 has a diameter about 100 mm.

Figure 35 dam structure outlet of CTD

In early spring, control structures on the tile headers remain open to permit free drainage and allow for improved soil aeration until after field operations or, in some cases, until after crops are adequately established. The structures will then be closed to restrict drainage until crops harvest.

Figure 36 Pipe used in WEBs project

Compared to CTD, UCTD is a conventional tile drainage system adopted worldwide, on fields in a naturally open status without human intervention.

CTD and UCTD are modelled through the TDR parameter in AnnAGNPS defined as a daily maximum discharge rate per unit area produced from the tile drainage system on a field (mm/d) (Bingner et al., 2007), which is used for tile drain flow calculations if applicable. In the model, TDR only has an effect on cropland fields; other areas such as forest, pasture, urban and water do not employ tile drainage. Theoretically, TDR can be compared to a valve of the tile drainage system that controls the water table in a tile drained field.

6.2.2 Determination of TDR of CTD

The crux of the CTD scenario is to set proper TDRs that can correctly represent the physical conditions in CTD fields. In order to evaluate the impact of CTD on water quality and crop yields, the WEBs project chose 8 experimental sites shown in Figure 35 in the SNW to observe and collect experimental data. Four of the sites, Sites 1, 3, 6 and 8 are equipped with controllable facilities operated as CTD. These sites had CTD installed at the conditions specified in Section 6.2.1.

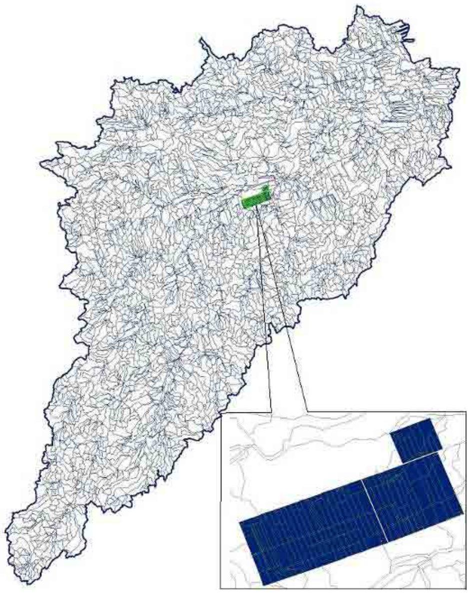


Figure 37 Locations of WEBs experimental sites

Average monthly flows for growing season consisting of May, June, July, August, September, October and November were calculated based on four years of observations from 2006 to 2009 in the experimental CTD Sites 1, 3 and 8. Data from Site 6 were not used due to a construction issue and measurements were significantly different from those obtrained in the adjacent fields. The units of the. daily flows were transformed from m^3/s to mm/d in correspondence with the unit of the TDR parameter of the model, thus CTD rates can be calculated based on these experimental flow data. TDRs and standard deviations (STD) are given in Table 6.1.

Table 6.1 TDRs for CTD in sites 1, 3, and 8

Month	TDR (mm/d)	STD
May	0.053	0.456
June	0.108	0.344
July	0.146	0.730
August	0.015	0.093
September	0.235	0.767
October	0.392	0.813
November	0.338	0.722

In experimental fields, outlets are usually closed except for flooding or waterlogging conditions in the growing season, so there are many zero daily flows. As a result, STD values of TDRs based on daily flows are large.

It was too onerous and beyond the scope of this work. to adjust TDRs on a daily basis in the model; therefore the average monthly TDR was used.

6.2.3 Determination of TDR of UCTD

Yuan et al. (2006) suggested a drainage rate of 12.7 mm/d as a normal TDR based on local conditions in the research on the subsurface flow component for AnnAGNPS. In this research, eight rates, 0.01, 0.05, 0.10, 0.50, 1, 10, 50, and 100 (mm/d), were evaluated for 2001, the year for which the best data set was available for all simulated parameters. The results in Figures 36-39 show that all exports from the sites no longer depend on the TDR once it reaches a value near 12 mm/d.

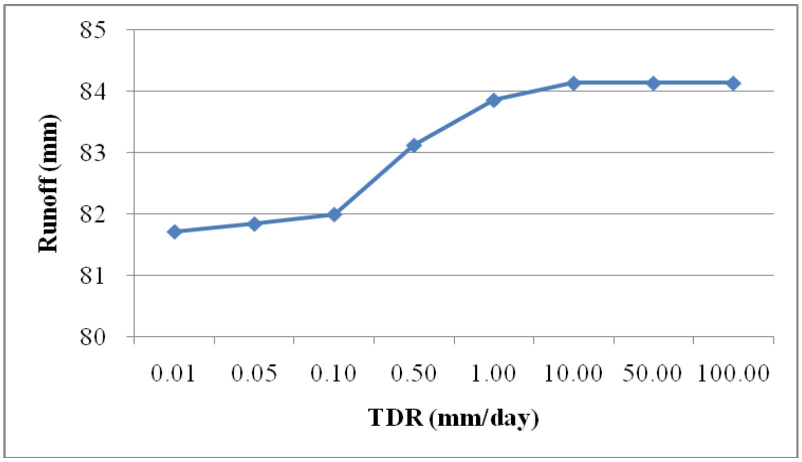


Figure 38 Runoff at different TDRs

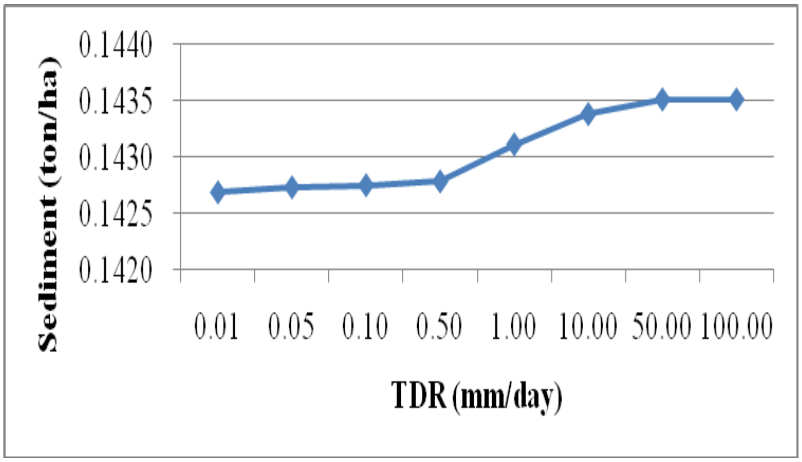


Figure 39 Sediment at different TDRs

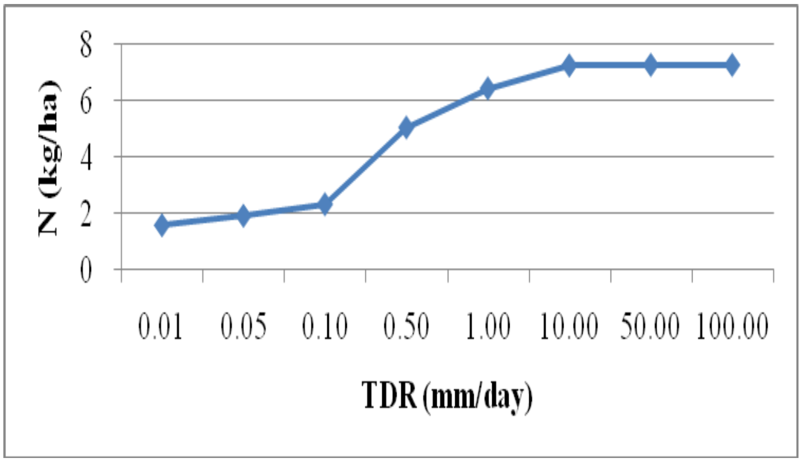


Figure 40 N yield at different TDRs

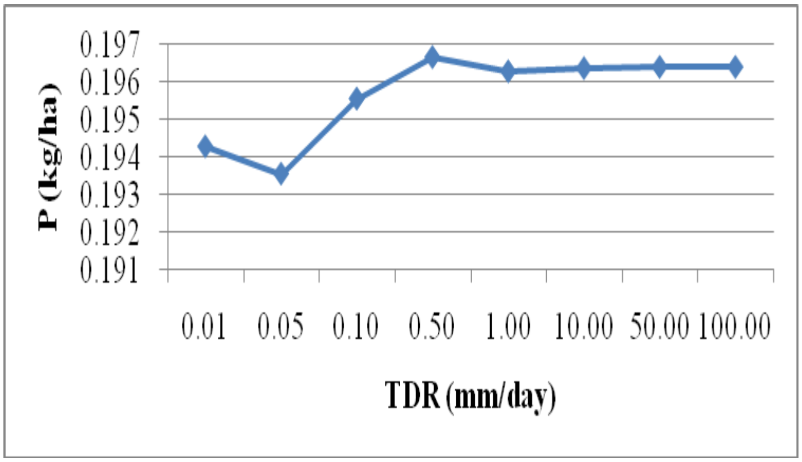


Figure 41 P yield at different TDRs

Based on the above, the value of 12.7 mm/d was set as the TDR of UCTD fields in this research.

6.2.4 Potential CTD areas in the watershed

6.2.4.1 Standard for potential CTD areas

Normally, surface slopes of soils in fields that are capable of supporting water table control are less than 2% (USDA, 2001). Slopes of 1% or less are recommended by ADMSTF (2003) consisting of representatives from industry, universities, USDA-ARS, and USDA-NRCS.

6.2.4.2 Calculating Procedure

The key step to distinguish potential CTD areas from common croplands is to calculate the slope of croplands. The whole calculating procedure is a quite complicated series of operations; therefore, only the main steps are listed as follows:

- Delineating the DEM into cells (subwatersheds) in ArcView
- Calculating the slope of each cell
- Converting the raster into a vector (shape file)
- Assigning land use type to each cell
- Summarizing croplands with slope more than 1%

6.2.4.3 Calculating Results

Potential cropland areas for implementing a tile drain system in the watershed as calculated are shown in Figure 40. The CTD scenario in the model was only applied to the potential croplands that have surface slopes equal to or less than 1%.

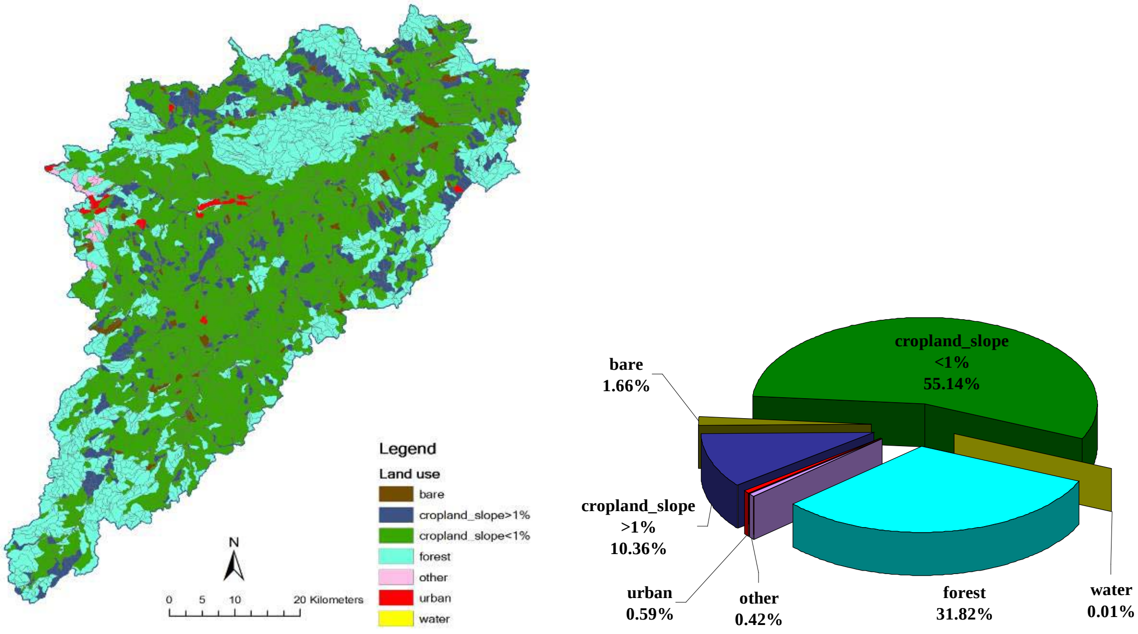


Figure 42 Potential controlled tile drainage area

The result of the calculation indicates that most croplands in the SNW are suitable for establishing CTD facilities. Of the total 2475 km^2 croplands, there are 2083 km^2 potential croplands that could accommodate CTD practice.

CHAPTER 7

SIMULATION RESULTS AND DISCUSSION

7.1 Introduction

In order to assess CTD implementation impacts on surface water quantity and water quality parameters in the SNW, two scenarios, UCTD and CTD, described in Section 6.1 were applied to potential croplands in the growing season, from May to November, in 2006 and 2007 on the basis of annual average considering data observation period and simulation computation time. The UCTD for evaluation is the simulation results from the TDR of UCTD applied to the calibrated and validated model based on the same timeline, and objects being compared are the results of the model with the TDR of CTD.

7.2 Runoff

Compared to the amount of runoff generated from the UCTD scenario, approximately 2×10^7 Mg water from the CTD scenario remained within CTD fields instead of discharging from crop fields during the two growing seasons in 2006 and 2007 as shown in Figure 41. By comparison to the total runoff of the UCTD scenario, the reduction rate from the CTD scenario is 2.70%.

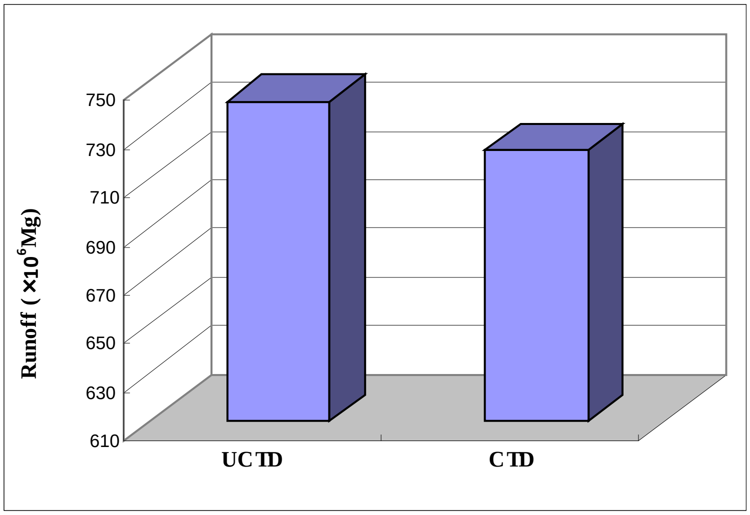


Figure 43 Runoff of CTD and UCTD scenario

Although the rate does not appear to be significant, the absolute difference between the UCTD and CTD scenarios during the months of May-November is conspicuous relative to the scale of the CTD fields; this has important implications for crop growth.

This simulation on runoff on the basis of the current experiments of WEBs project indicates that the CTD technique does directly reduce runoff discharged out of crop fields; therefore, crops within the CTD fields can benefit from the saved water .throughout the growing season and have more than sufficient amounts of water to support growth during all phases of growth.

7.3 Sediment

The model provides more details on sediment than runoff, which consists of three components, clay, silt and sand. Specifically in the SNW, clay contributes primarily to the total amount of sediment in comparison to the other two minor components, silt and sand, as Figure 42 displays.

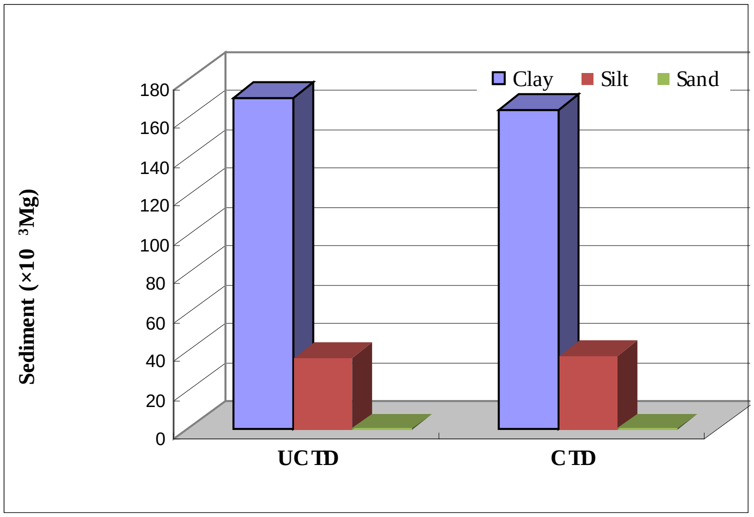


Figure 44 Components of sediment simulated by the model

These three components act in different ways on the CTD scenario. For the major component, clay, the trend is positive, the reduction rate of clay is 3.29%; whereas the other two minor silt and sand components have negative relationships (i.e., they increase) with the scenario, and the rates are −3.26 and −1.72%, respectively.

In total as shown in Figure 43, the gross annual load of sediment including clay, silt and sand from the UCTD scenario is 207377×10^3 Mg, and the amount from the CTD scenario is 202995×10^3 Mg. The difference between these two scenarios is 4382×10^3 Mg. The total reduction rate is 2.11%. This rate is similar to the rate of decrease of runoff.

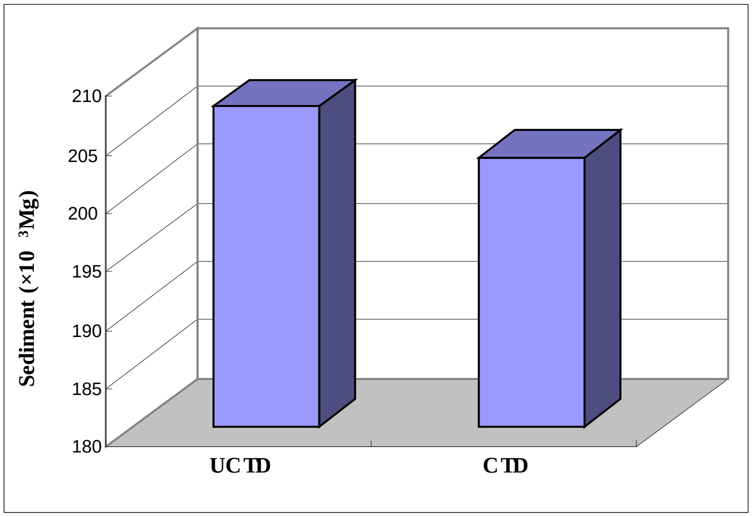


Figure 45 Total sediment of CTD and UCTD scenario

Similar to runoff, the simulation result denotes that the CTD technique can prevent soil erosion from crop fields through controlling water management on field.

7.4 Nitrogen

The model can simulate two types of N, attached N and dissolved N. They have different reduction rates depicted in Figure 44. Compared to the UCTD scenario, the reduced amount of attached N discharged to receiving stream is 16.5×10^3 kg, and the reduction rate is 3.16%; there are 1079×10^3 kg of dissolved N reduced by the CTD, and its reduction rate is much higher than attached N, which reaches 37.4% in the simulation result.

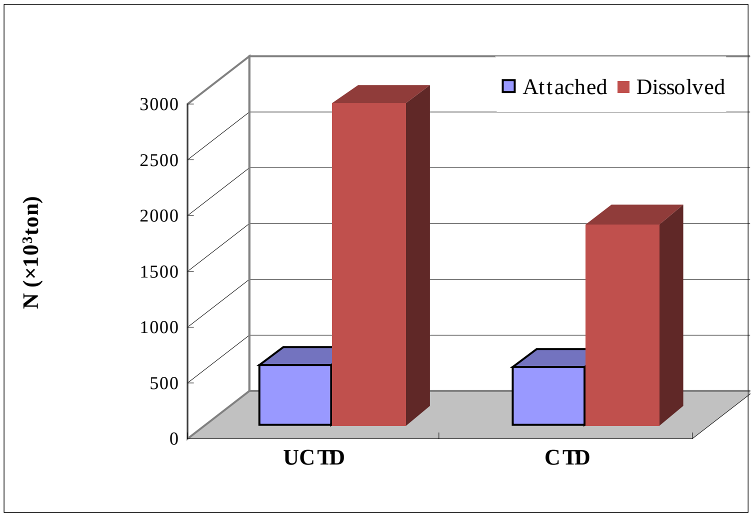


Figure 46 Components of N simulated by the model

Figure 44 indicates that dissolved nitrogen contributes a large portion to the reduction compared to attached nitrogen. The primary reason is denitrification as discussed in Section 3.1.2.4.

According to the above, although both the attached N and the dissolved N have different reduction rates in the CTD scenario; both of them have a positive relationship with the CTD scenario. The model simulates several major nitrogen losses such as soluble inorganic N in runoff, leaching, denitrification, and sediment-bound organic N from soil erosion. In CTD croplands, the CTD technique retains water, sediment and nitrogen instead of discharging them. The reduced total N from the CTD crop fields is approximately1095 $\times 10^3$ kg, and the reduction rate is 32.2% within two growing seasons in 2006 and 2007.

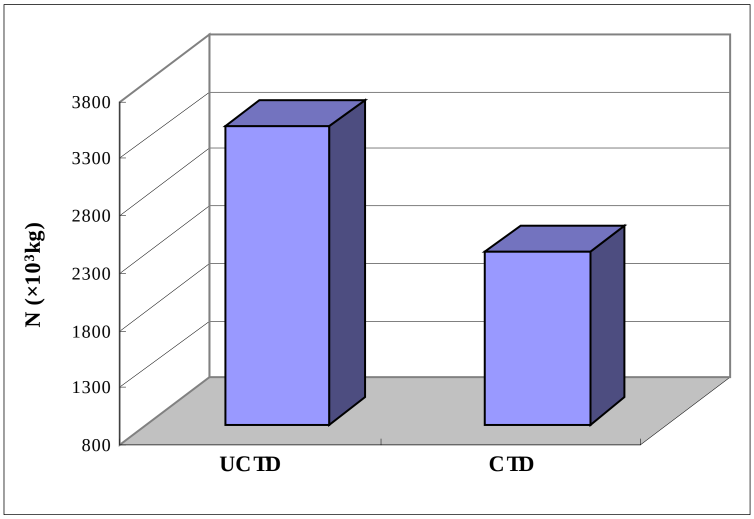


Figure 47 Total N of CTD and UCTD scenarios

This simulation result reveals that the CTD technique can effectively reduce total N discharge from crop fields to streams. Nitrogen losses were prevented by CTD facility from discharging out of croplands. Instead, nitrogen takes part in supporting crops growth and denitrification inside croplands.

7.5 Phosphorus

Similar to N as discussed above, the model is capable of simulating attached P and dissolved P. For the attached P, the simulation result denotes it has a positive relationship with the CTD practice. The reduced amount of attached P is 1724 kg, and the reduced rate is 4.75%. However, for dissolved P the simulation result indicates that dissolved P has a negative relationship with the CTD practice. The reduced amount is –2981 kg, and the reduced rate is –2.54%. Figure 46 shows the details of these reductions.

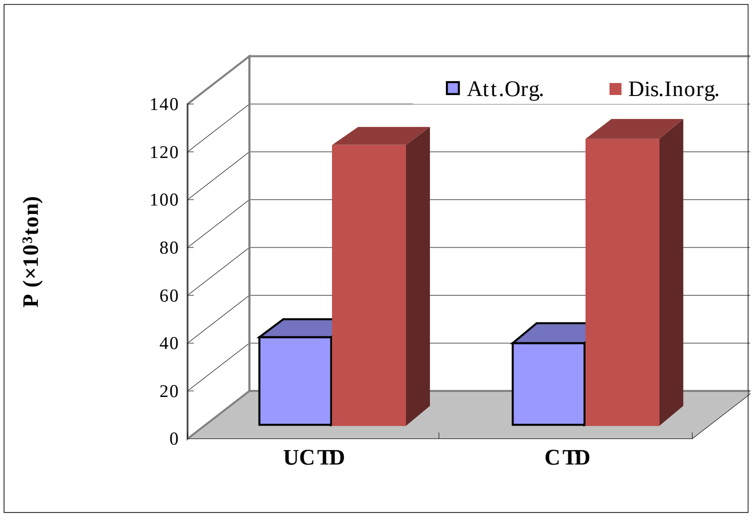


Figure 48 Components of P simulated by the model

By reason of the reduced amount and rate of dissolved P that has negative relationship with the CTD are much more than those of attached P that has positive relationship with the CTD, the reduced total P and rate are also inversely related to the CTD. The reduced total P is –1256 kg, and the reduced rate is –0.82% as Figure 47 shows.

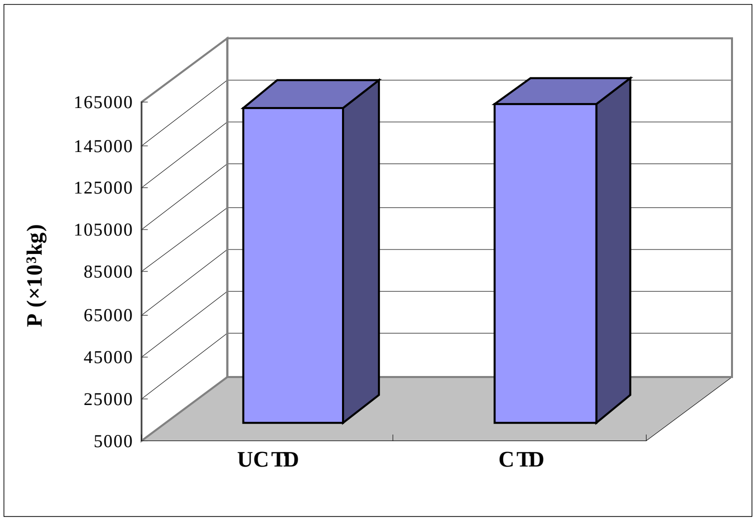


Figure 49 Total P of CTD and UCTD scenarios

This simulation on P does not agree with the actual observation from fields resulting from deficiencies of simulating dissolved P, the major part of the total P. Experimental observations from WEBs denotes that CTD reduced total phosphorus export by 56% in a growing season on average over 2006-2009 at field scale (Sunohara et al., 2010). This phenomenon verified that there are limitations in simulating P processes using AnnAGNPS model as discussed in Section 5.2.5.

7.6 Summary

The general results of the AnnAGNPS simulations of UCTD and CTD scenarios in the growing seasons of 2006 and 2007are shown in Table 7.1.

Table 7.1 Simulation results of UCTD and CTD

	Runoff	Sediment	N (kg)			P (kg)		
	(Mg)	(Mg)	Attached	Dissolved	Total	Attached	Dissolved	Total
UCTD	741×10^6	20.7×10^4	52.4×10^4	28.8×10^5	34.1×10^5	36264	11.7×10^4	15.4×10^4
CTD	721×10^6	20.3×10^4	50.7×10^4	18.0×10^5	23.1×10^5	34540	12.0×10^4	15.5×10^4
Reduced amount	20.0×10^6	43.8×10^2	16.5×10^3	10.8×10^5	11.0×10^5	17.2×10^2	29.8×10^2	12.6×10^2
Reduced rate (%)	2.7	2.1	3.2	37.4	32.2	4.8	-2.5	-0.82

This simulation denotes that the CTD scenario can reduce runoff, sediment and N losses from agricultural fields in the watershed through managing water table of croplands. Specifically, it can significantly prevent N loss from crop fields, and the reduced rate reaches 32.2%.

CHAPTER 8

CONCLUSIONS AND RECMANDATIONS

8.1 Conclusions

In this research, the AnnAGNPS model was introduced to evaluate the impact of CTD on surface water quality through the CTD scenario and UCTD scenario designed on the basis of observations from WEBs project experimental sites in the SNW. The model is a comprehensive watershed level evaluation tool consisting of 500 types of parameters involved in a wide range of areas such as soil, hydrology, hydraulics, agriculture, meteorology, environment, GIS, programming among others. Accordingly this research demands massive investigations and observed data supporting a realistic surface water quality model that can well characterize physical processes in the watershed.

The performance of calibration and validation shows excellence of the model setup for the SNW based on the Nash-Sutcliffe values obtained compared to typical literature values. AnnAGNPS can be used to assess impacts of CTD on surface water quality on nitrogen issues and by extension impacts on aquatic ecosystems and cost benefit to producers in this watershed.

These results of the research indicate that CTD can significantly improve surface water quality by reducing nitrogen losses from agricultural areas in a watershed. Compared to the reduction of nitrogen, reductions of runoff and sediment appear to be marginal. However, these reductions are also considerable regarding them only from potential CTD fields and their huge absolute values.

Two scenarios, UCTD and CTD that would be applied to potential croplands for CTD, were evaluated in growing seasons of 2006 and 2007. By comparison of total runoff from the UCTD scenario, the reduction rate by the CTD scenario is 2.7%; approximately 2×10^7 Mg water remain within CTD fields instead of discharging. The gross discharge of sediment including clay, silt and sand reduced by 4382×10^3 Mg. The reduction rate for discharge of sediment is 2.1%. The reduced total nitrogen discharge is 1095×10^3 kg, and the reduction rate reaches 32.2%. This rate shows that CTD can effectively prevent nitrogen applied to crop fields from discharging to receiving streams, subsequently alleviating surface water pollution.

However, for the other key nutrient of phosphorus, reductions are not commensurate with the actual observations from experimental fields resulting from AnnAGNPS deficiencies in simulating the major components of total and dissolved phosphorus.

This research has examined the impact of CTD on surface water quality at watershed level. The model built in this research is a workable method to evaluate the impact of CTD in the watershed. Results of the research will be capable of helping issue recommendations to policy-makers on proper management of the watershed. There are numerous benefits offered by CTD verified by results from this research to the community, environment, and regional economy at watershed scale, which are not limited to improved surface water quality in rivers and lakes, but also reduced water demand for irrigation, reduced need for fertilizer, and providing a healthy and fruitful local habitat for residents.

8.2 Recommendations for Further Research

This research is based on historical observed data and experimental observations from WEBs project sites in the SNW. There is a need to apply the modeling efforts and existing field experiments to a variety of climate and land use scenarios to further assess the adaptability of impact of CTD under dynamic conditions. Furthermore, such modeling outputs should be linked to river water quality models to predict how CTD impacts on aquatic ecosystem function.

REFERENCES

Abbott, M.B., J.C. Bathurst, J.A. Cunge, P.E. O'Connell, and J. Rasmussen. 1987a. An introduction to the European Hydrological System - Système Hydrologique Européen, "SHE", 1: History and philosophy of a physically based distributed modeling system. *J. Hydrology* 87(1-2): 45-59.

Abbott, M.B., J.C. Bathurst, J.A. Cunge, P.E. O'Connell, and J. Rasmussen. 1987b. An introduction to the European Hydrological System - Système Hydrologique Européen, "SHE", 2: Structure of a physically based distributed modeling system. *J. Hydrology* 87(1-2): 61-77.

AC 2007 Soil Landscapes of Canada Version 3.1.1. Ottawa, Agriculture and Agri-Food Canada. Available at: http://sis.agr.gc.ca/cansis/nsdb/slc/v3.1.1/intro.html (accessed Mar. 2, 2009).

Arnold, J.G., J.R. Williams, A.D. Nicks, and N.B. Sammons. 1990. SWRRB: A basin scale simulation model for soil and water resources management. Texas A&M Univ. Press, College Station, TX.

Arnold, J.G., J.R. Williams, and D.R. Maidment. 1995. Continuous-time water and sediment-routing model for large basins. *J. Hydraulic Eng*. 121(2): 171-183.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. *J. American Water Resources Assoc*. 34(1): 73-89.

Beasley, D.B., Huggins, L.F., and Monke, E.J. (1980). "ANSWERS: a model for watershed planning." *Trans. ASAE*, 23(4), 938-944.

Bingner, R.L., F.D. Theurer and Y. Yuan 2007. AnnAGNPS Technical Processes. Available at: ftp://199.133.90.201/pub/outgoing/AGNPS/AGNPS_Web_Files/pdf_files/AnnAGNPS_Technical_Documentation.pdf Accessed June 15, 2009.

ADMSTF 2003. Agricultural Drainage Water Management Systems for Improving Water Quality and Increasing Crop Production. Available at: http://www.ag.ohio-state.edu/~usdasdru/ADMS/Drainage%20Fact%20Sheet2_files/Drainage%20Fact%20Sheet_post-final%20version.pdf Accessed July 15, 2010.

Bosch, D., F. Theurer, R. Bingner, G. Felton and I. Chaubey. 1998. Evaluation of the AnnAGNPS water quality model. ASAE Paper No. 98-2195. St. Joseph, MI:ASABE.

Bouraoui, F., and T.A. Dillaha. 1996. ANSWERS-2000: Runoff and sediment transport model. *J. Environ. Eng*. 122(6): 493-502.

CH2MHILL 2001 *Eastern Ontario Water Resources Management Study Final Report*. CH2MHILL, Ottawa, ON.

Das S, Rudra RP, Gharabaghi B, Gebremeskel S, Goel PK, and Dickinson WT. 2008. Applicability of AnnAGNPS for Ontario conditions. Canadian Biosystems Eng., vol. 50, no. 1, 2008, 1-11.

EC 2008 *Climate Data Online*. ON: Environment Canada. Available at: http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html. (Accessed Feb. 2, 2009).

EC 2008 *Archived Hydrometric Data*. ON: Environment Canada. Available at: http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm. (Accessed on Feb. 12, 2009.)

Fleming, R., Fraser, H. 1999. Nitrate and phosphorus levels in selected surface water sites in Southern Ontario–1964-1994. Ridgetown College University of Guelph. 1-16.

Garbrecht, J. and L.W. Martz, 1997. TOPAZ Version 3.1: An automated digital landscape analysis tool for topographic evaluation, drainage identification, watershed segmentation and subcatchment parameterization - Overview. Grazinglands Research Laboratory, USDA, Agricultural Research Service, El Reno, OK.

Graham, D.N. and M.B. Butts, 2005. Chapter 10 Flexible Integrated Watershed Modeling With MIKE SHE. In: Watershed Models, V.P. Singh and D.K. Frevert (Editors). CRC Press, Boca Raton, FL, 245-272.

Havlin, J. L., J. D. Beaton, S. L. Tisdale and W. L. Nelson. 1999. Soil Fertility and Fertilizers. 6th Edition. Prentice Hall. Upper Saddle River, NJ.

Johnson, G.L., C. Daly, G.H. Taylor and C.L. Hanson. (2000). Spatial variability and interpolation of stochastic weather simulation model parameters. *J. Appl. Meteor.*, 39, 778-796.

Knisel, W.G., ed. 1980. CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management system. Conservation Research Report No. 26. Washington, DC: USDA-SEA.

Leonard, R.A., W.G. Knisel, and D.A. Still. 1987. GLEAMS: Groundwater loading effects on agricultural management systems. *Trans. ASAE* 30(5): 1403-1428.

Lim, K.J., Engel, B.A., Tang, Z., Choi, J., Kim, K.-S., Muthukrishnan, S. and Tripathy, D. (2005), AUTOMATED WEB GIS BASED HYDROGRAPH ANALYSIS TOOL, WHAT. *Journal of the American Water Resources Association*, 41: 1407–1416.

Liu, J., L. Zhang, Y. Zhang, H. Hong, and H. Deng. 2008. Validation of an agricultural non-point source (AGNPS) pollution model for a catchment in the Jiulong River watershed, China. *J Environ Sci (China)*. 20(5):599-606.

Loague K. and Green R.E. 1991 Statistical and graphical methods for evaluating solute transport models: Overview and application. *J. Contaminant Hydrol.* 7(1-2), 51-73.

McCuen, R.H. 1973. The role of sensitivity analysis in hydrological modeling. J. Hydrology. 18, 37–53.

MIKE SHE. In Watershed Models, Eds. V.P. Singh & D.K. Frevert 245-272, CRC Press.

Nash J.E. & Sutcliffe J.V. 1970 River flow forecasting through conceptual models: Part I. A discussion of principles. *J. Hydrol.* 10(3), 282-290.

Neitsch, S.L., J.G. Arnold, J. R. Kiniry, and J.R. Williams. 2005. *Soil and Water Assessment Tool Theoretical Documentation Version 2005*. Temple, Texas.

Novotny, V. 2003. Water quality: Diffuse Pollution and Watershed Management 2nd edition. Wiley, New York, NY.

Parker, G.T., Droste, R.L., and Kennedy, K.J., Modeling the effect of Agricultural Best Management Practices on Water Quality under various Climatic Scenarios, Journal of Environmental Engineering and Science, National Research Council. Ottawa, ON 2008

Polyakov, V., A. Fares , D. Kubo , J. Jacobi , C. Smith, Evaluation of a non-point source pollution model, AnnAGNPS, in a tropical watershed. 2007.Environmental Modelling & Software, v.22 n.11, p.1617-1627

Pommainville A. 2007 *Survey on Agricultural Management Practices*. Alfred, ON, Canada.

Renard K.G., Foster G.R., Weesies G.A., McCool D.K. and Yoderordinators D.C. 1997 Predicting Soil Erosion by Wwater: A guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). U.S. Department of Agriculture, Agriculture Handbook No. 703, 404 pp.

Schut L.W. and Wilson E.A. 1987. The Soils of the Regional Municipality of Ottawa-Carleton. Ministry of Agriculture and Food Ontario, Ottawa, Canada, p. 96.

South Nation Conservation Authority. 2006. State of the Nation. ON. P2.

Sunohara, M. Youssef, M.A., Topp, E. and Lapen, D.R. *in Proceeding of 9th International Drainage Symposium held jointly with CIGR and CSBE/SCGAB*, Quebec, 2010, IDS-CSBE-100175 (2010)

Theurer, F.D. and C.D. Clarke. (1991). Wash load component for sediment yield modeling. In Proceedings of the fifth federal interagency sedimentation conference, March 18-21, 1991, pp. 7-1 to 7-8.

USDA, Soil Conservation Service. 1972. National Engineering Handbook. Hydrology Section 4, Chapters 4-10, 16, 19. Washington, DC.

USDA, Natural Resources Conservation Service. 2001. National Engineering Handbook. Drainage Section 624, Chapters 10. Washington, DC.

USEPA. 2008. Better Assessment Science Integrating Point and Nonpoint Sources, BASINS Version 4.0 User's Manual. EPA 823-C-07-001. US Environmental Protection Agency, Office of Water, Washington, DC.

Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. A modeling approach to determine the relationship between erosion and soil productivity. *Trans. ASAE* 27(1): 129-144.

Willianms, J.R., A.D. Nicks, and J.G. Arnold. 1985 Simulator for water resources in rural basins. *Journal of Hydraulic Engineering* 111(6): 970-986.

Young, R.A., C.A. Onstad, D.D. Bosch, and W.P. Anderson. 1989. AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. *Journal of Soil and Water Conservation*, 44(2):168-173.

Yuan, Y., R.L. Bingner, and R.A. Rebich. 2003. Evaluation of AnnAGNPS nitrogen loading in an agricultural watershed. *J. American Water Res. Assoc.* 39(2): 457-466.

Yuan, Y.P., Bingner, R.L., Rebich, R.A., 2001. Evaluation of AnnaGNPS onMississippi Delta MSEA watersheds. Transactions of the ASAE 44 (5).

Yuan, Y., R.L. Bingner, and F.D. Theurer. 2006. Subsurface Flow Component for AnnAGNPS. *Applied Engineering in Agriculture*, 22(2): 231-241.

Yuan, Y., R.L. Bingner, F.D. Theurer, R.A. Rebich, and P.A. Moore. 2005. Phosphorus Component in AnnAGNPS. *Transactions of the ASAE*, 48(6): 2145-2154.

APPENDIX A

DIGITAL ELEVATION MODEL

A.1 Description

Data storage and access information

File name: dem_nrvis

Type of data: raster digital data

Accessing the data

Size of the data: 589.009 MB

Data transfer size: 589.009 MB

Standards used to create this document

Standard name: FGDC Content Standards for Digital Geospatial Metadata

Standard version: FGDC-STD-001-1998

Horizontal coordinate system

Projected coordinate system name: NAD_1983_UTM_Zone_18N

Geographic coordinate system name: GCS_North_American_1983

Grid Coordinate System Name: Universal Transverse Mercator

UTM Zone Number: 18

Transverse Mercator Projection

Scale Factor at Central Meridian: 0.999600

Longitude of Central Meridian: -75.000000

Latitude of Projection Origin: 0.000000

False Easting: 500000.000000

False Northing: 0.000000

Planar Coordinate Information*Planar Distance Units:* meters

Coordinate Encoding Method: row and column

Coordinate Representation

Abscissa Resolution: 10.000000

Ordinate Resolution: 10.000000

Geodetic Model

Horizontal Datum Name: North American Datum of 1983

Ellipsoid Name: Geodetic Reference System 80

Semi-major Axis: 6378137.000000

Denominator of Flattening Ratio: 298.257222

Bounding coordinates in decimal degrees

West: -75.900666

East: -74.290282

North: 45.652779

South: 44.564918

In projected or local coordinates

Left: 429820.000000

Right: 555300.000000

Top: 5055470.000000

Bottom: 4935000.000000

Raster dataset information

Raster format: GRID

SDTS raster type: Grid Cell

Number of raster bands: 1

Number of cells on x-axis: 12548

Number of cells on y-axis: 12047

Number of cells on z-axis: 1

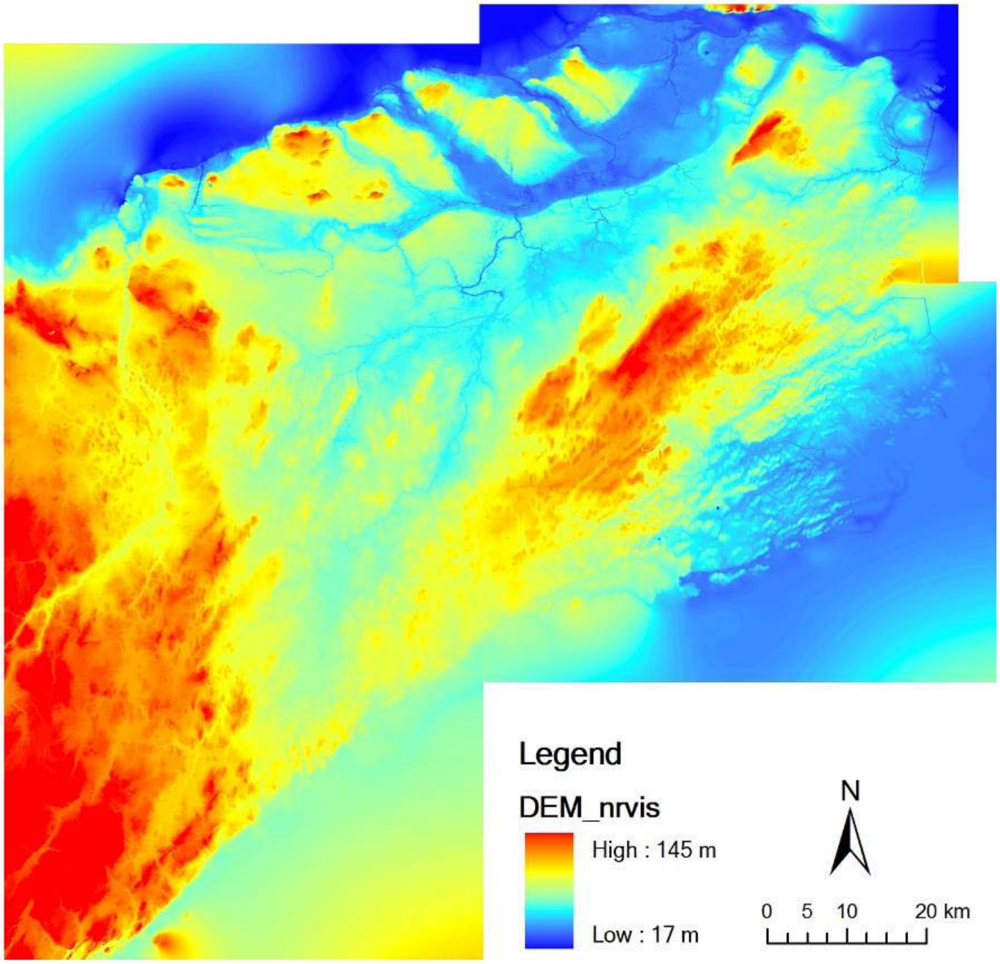
Number of bits per cell: 32

Cell Size

X distance: 10.000000

Y distance: 10.000000

A.2 DEM map



APPENDIX B

LANDUSE DATA INFORMATION

B.1 Description

Data storage and access information

File name: class7

Type of data: vector digital data

Location of the data:

Accessing the data

Size of the data: 112.763 MB

Data transfer size: 112.763 MB

Horizontal coordinate system

Projected coordinate system name: NAD_1983_UTM_Zone_18N

Geographic coordinate system name: GCS_North_American_1983

Grid Coordinate System Name:

Universal Transverse Mercator

UTM Zone Number: 18

Transverse Mercator Projection

Scale Factor at Central Meridian: 0.999600

Longitude of Central Meridian: -75.000000

Latitude of Projection Origin: 0.000000

False Easting: 500000.000000

False Northing: 0.000000

Planar Coordinate Information

Planar Distance Units: meters

Coordinate Encoding Method: coordinate pair

Coordinate Representation

Abscissa Resolution: 0.000000

Ordinate Resolution: 0.000000

Geodetic Model

Horizontal Datum Name: North American Datum of 1983

Ellipsoid Name: Geodetic Reference System 80

Semi-major Axis: 6378137.000000

Denominator of Flattening Ratio: 298.257222

Bounding coordinates in decimal degrees

West: -76.546437

East: -74.338544

North: 45.643175

South: 44.300408

In projected or local coordinates

Left: 379466.292452

Right: 551548.001022

Top: 5054403.038650

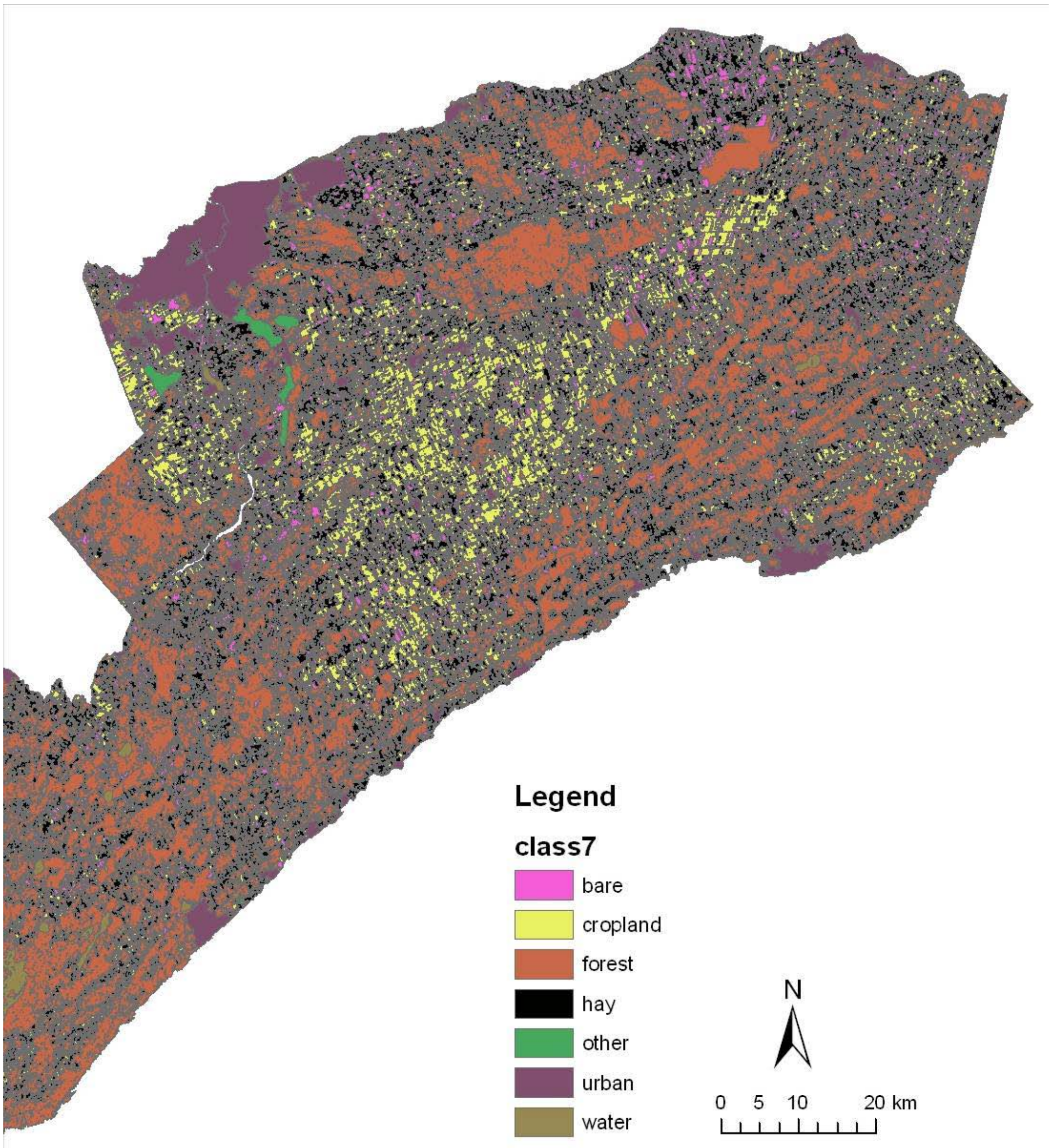
Bottom: 4906349.565226

Details for class7

Type of object: Feature Class

Number of records: 211832

B.2 Land use map



APPENDIX C

SOIL DATA INFORMATION

C.1 Description

Data storage and access information

File name: Soil_SN

Type of data: vector digital data

Accessing the data

Size of the data: 243.248 MB

Data transfer size: 243.248 MB

Horizontal coordinate system

Projected coordinate system name: NAD_1983_UTM_Zone_18N

Geographic coordinate system name: GCS_North_American_1983

System Name: Universal Transverse Mercator

UTM Zone Number: 18

Transverse Mercator Projection

Scale Factor at Central Meridian: 0.999600

Longitude of Central Meridian: -75.000000

Latitude of Projection Origin: 0.000000

False Easting: 500000.000000

*False Northing: 0.000000***Planar Coordinate Information**

Planar Distance Units: meters

*Coordinate Encoding Method: coordinate pair***Coordinate Representation**

Abscissa Resolution: 0.000000

*Ordinate Resolution: 0.000000***Geodetic Model**

Horizontal Datum Name: North American Datum of 1983

Ellipsoid Name: Geodetic Reference System 80

Semi-major Axis: 6378137.000000

Denominator of Flattening Ratio: 298.257222

Bounding coordinates in decimal degrees

West: -83.679122

East: -74.330611

North: 46.342264

South: 41.683423

In projected or local coordinates

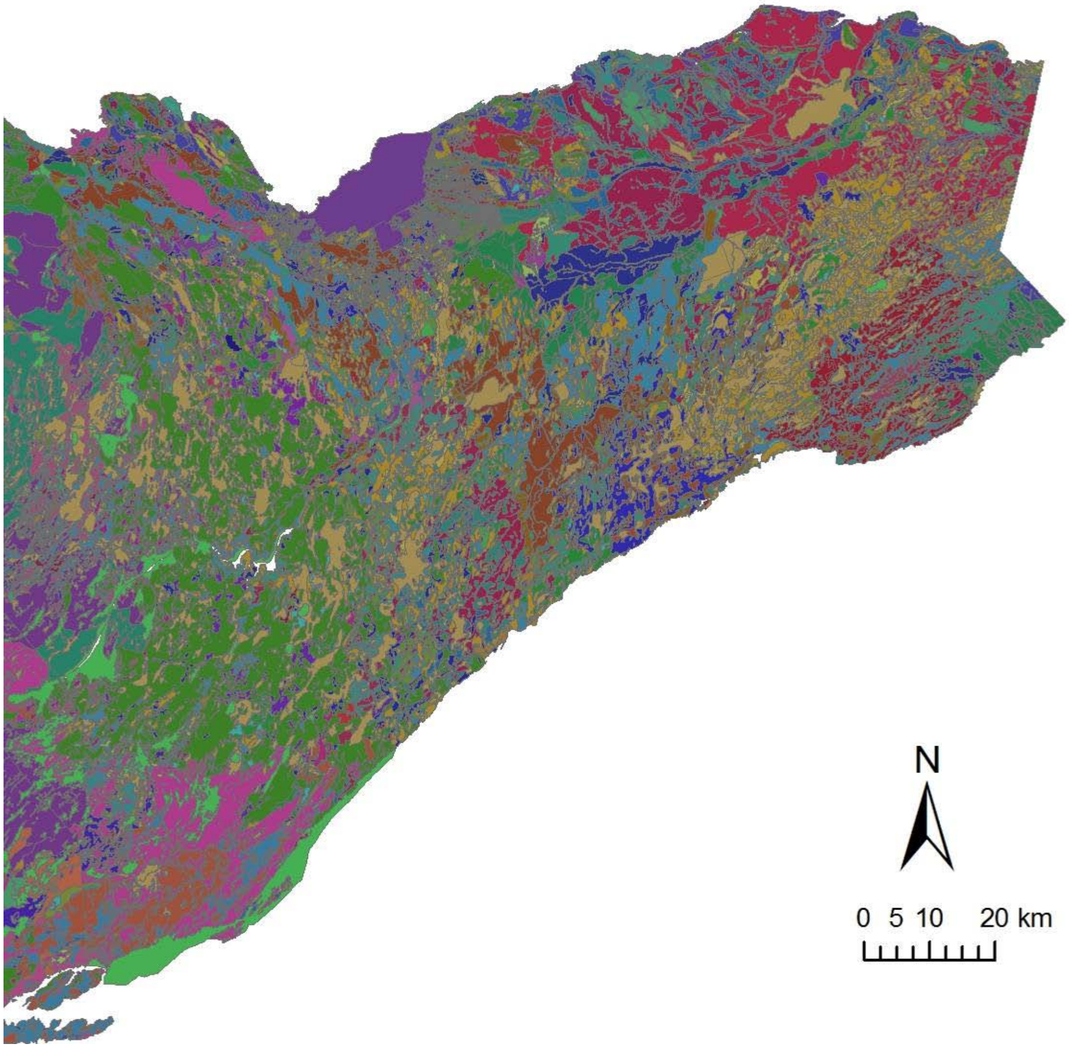
Left: -171808.996115

Right: 551513.624079

Top: 5132076.463188

Bottom: 4646197.903584

C.2 Soil map



APPENDIX D

MATLAB PROGRAMS FOR THE MODEL

D.1 Climate data format defining program

The format of the climate input data is very delicate. The model will not recognize the climate input data if there is extra or missing one space sign in the file. At the same time, the climate input data file normally contains vast amounts of data; this program can handle automatically the format transformations.

```
% File name: refomat.m
% Transform the format of historical climate data into the prescribed
% format of the model
% Mar. 18, 2009

clear
clc

% Read year from Excel file
year=xlsread('otta0708.xls','otta0708','A1:A731');

% Read month from Excel file
month=xlsread('otta0708.xls','otta0708','B1:B731');

% Read date from Excel file
date=xlsread('otta0708.xls','otta0708','C1:C731');

% Read precipitation from Excel file
p=xlsread('otta0708.xls','otta0708','D1:D731');

% Read max temperature from Excel file
tmax=xlsread('otta0708.xls','otta0708','E1:E731');

% Read min temperature from Excel file
tmin=xlsread('otta0708.xls','otta0708','F1:F731');

% Read radiation from Excel file
r=xlsread('otta0708.xls','otta0708','G1:G731');

% Define climate array =[year;month;date;p;tmax;tmin;r];
m=year';
n=month';
d=date';
o=p';
x=tmax';
y=tmin';
z=r';

climate=[m;n;d;o;x;y;z];

% Generate a txt file to store formatted climated
```

```
fid = fopen('otta0708.txt', 'wt');
fprintf(fid,'%4.0f %6.0f %4.0f %9.1f %11.1f %10.1f %10.1f\n', climate);
fclose(fid);
```

D.2 Model output processing program

For version 4.0, the STEAD can not process big value more than one hundred millions. This program intended to summarize annual and monthly amount from the output of the model.

```
% File name:summary.m
% Calculation of sum of year and month of direct runoff and base flow
% Aug. 20 2009

clear;
clc;

% Define variables
Runoff_Temp=0; % Direct runoff
Sediment_Temp=0; % Total B&B
Nitrogen_Temp=0; % Total itrogen
Phosphrus_Temp=0; % Total Phosphrus

Record_2=1; % Length of record;

% Define arrays to save data
Month=[]; % Month array
Year=[]; % Year array
Runoff=[]; % Runoff array
Sediment=[]; % Sediment array
Nitrogen=[]; % Nitrogen array
Phosphrus=[]; % Phosphorus array
Result=[]; % Array of calculation result

% Get original data from the output file generated by AnnAGNPS
Trunk=xlsread('Summary','AnnAGNPS_TXT_Gaging_Station_Dat','A5:Y1072');

% Set start point
i=1;
Record_1=length(Trunk);

%%%%%%%%%%%%%%%%%Calculating Month Summary%%%%%%%%%%%%%%%%%%

while i<Record_1&&Trunk(i+1,3)==Trunk(i,3)
    if i<Record_1-31
       while Trunk(i+1,1)==Trunk(i,1)
             Runoff_Temp=Runoff_Temp+Trunk(i,8);
             Sediment_Temp=Sediment_Temp+Trunk(i,15);
             Nitrogen_Temp=Nitrogen_Temp+Trunk(i,18);
             Phosphrus_Temp=Phosphrus_Temp+Trunk(i,22);
             i=i+1;
       end

             Runoff(Record_2)=Runoff_Temp+Trunk(i,8);
```

```
                Sediment(Record_2)=Sediment_Temp+Trunk(i,15);
                Nitrogen(Record_2)=Nitrogen_Temp+Trunk(i,18);
                Phosphrus(Record_2)=Phosphrus_Temp+Trunk(i,22);
                Record_2=Record_2+1;
                Runoff_Temp=0;
                Sediment_Temp=0;
                Nitrogen_Temp=0;
                Phosphrus_Temp=0;
                i=i+1;
    else

      for j=i:Record_1-1
          Runoff_Temp=Runoff_Temp+Trunk(i,8);
          Sediment_Temp=Sediment_Temp+Trunk(i,15);
          Nitrogen_Temp=Nitrogen_Temp+Trunk(i,18);
          Phosphrus_Temp=Phosphrus_Temp+Trunk(i,22);
          i=i+1
          j=j+1;
      end

          Runoff(Record_2)=Runoff_Temp+Trunk(i,8);
          Sediment(Record_2)=Sediment_Temp+Trunk(i,15);
          Nitrogen(Record_2)=Nitrogen_Temp+Trunk(i,18);
          Phosphrus(Record_2)=Phosphrus_Temp+Trunk(i,22);
   end
end

a=Runoff';
b=Sediment';
c=Nitrogen';
d=Phosphrus';
y=[a,b,c,d];

%%%%%%%%%%%%%%%%%Calculating Year Summary%%%%%%%%%%%%%%%%%%

m=1;
n=1;
Record_3=1;
Runoff_Temp_Year=0;
Sediment_Temp_Year=0;
Nitrogen_Temp_Year=0;
Phosphrus_Temp_Year=0;

while m<=length(Runoff)
    for n=m:m+11
        Runoff_Temp_Year=Runoff_Temp_Year+Runoff(n);
        Sediment_Temp_Year=Sediment_Temp_Year+Sediment(n);
        Nitrogen_Temp_Year=Nitrogen_Temp_Year+Nitrogen(n);
        Phosphrus_Temp_Year=Phosphrus_Temp_Year+Phosphrus(n);

        m=m+1;
        n=n+1;

    end
```

```
    Runoff_Year(Record_3)=Runoff_Temp_Year;
    Sediment_Year(Record_3)=Sediment_Temp_Year;
    Nitrogen_Year(Record_3)=Nitrogen_Temp_Year;
    Phosphrus_Year(Record_3)=Phosphrus_Temp_Year;

    Runoff_Temp_Year=0;
    Sediment_Temp_Year=0;
    Nitrogen_Temp_Year=0;
    Phosphrus_Temp_Year=0;

    Record_3=Record_3+1;

end

% Define variables
e=Runoff_Year';
f=Sediment_Year';
g=Nitrogen_Year';
h=Phosphrus_Year';

x=[e,f,g,h];

% Write calculation result to file
xlswrite('simulation',x,'Year');
xlswrite('simulation',y,'Month');
```

APPENDIX E

AnnAGNPS INPUT FILE LAYOUT

(Extracted from Input File Specifications (2007))

The AnnAGNPS input header sections can be assembled in any order except that the first record must be the AnnAGNPS ID and the last must be End Data:. To assist the new user of the program, a suggested order is offered.

File ID

AnnAGNPS ID
Watershed Data

Simulation Period Data

Simulation Period Data

Cell Related Data

Cell Data

Field Related Data

Field Data
Management Sequence Data
Management Schedule Data
ManagementOperation Data
Contour Data
Irrigation Application Data
Fertilizer Application Data
Pesticide Application Data
Strip Crop Data
Tile Drain Data

Reach Related Data

Reach Data
Reach Geometry Coefficients
Reach Nutrient Half-life
Impoundment Data

Other Pollutant Source Data

Aquaculture Pond Data
Aquaculture Pond Management Schedule Data
Feedlot Data
Feedlot Management Data
Field Pond Data
Gully Data
Point Source Data

Reference Data

Crop Data
Fertilizer Reference Data

Non-Crop Data
Pesticide Reference Data
Runoff Curve Number Data
Soil Data

Winter Bouts Data

Winter Bouts Data

Output Related Data

Output Options

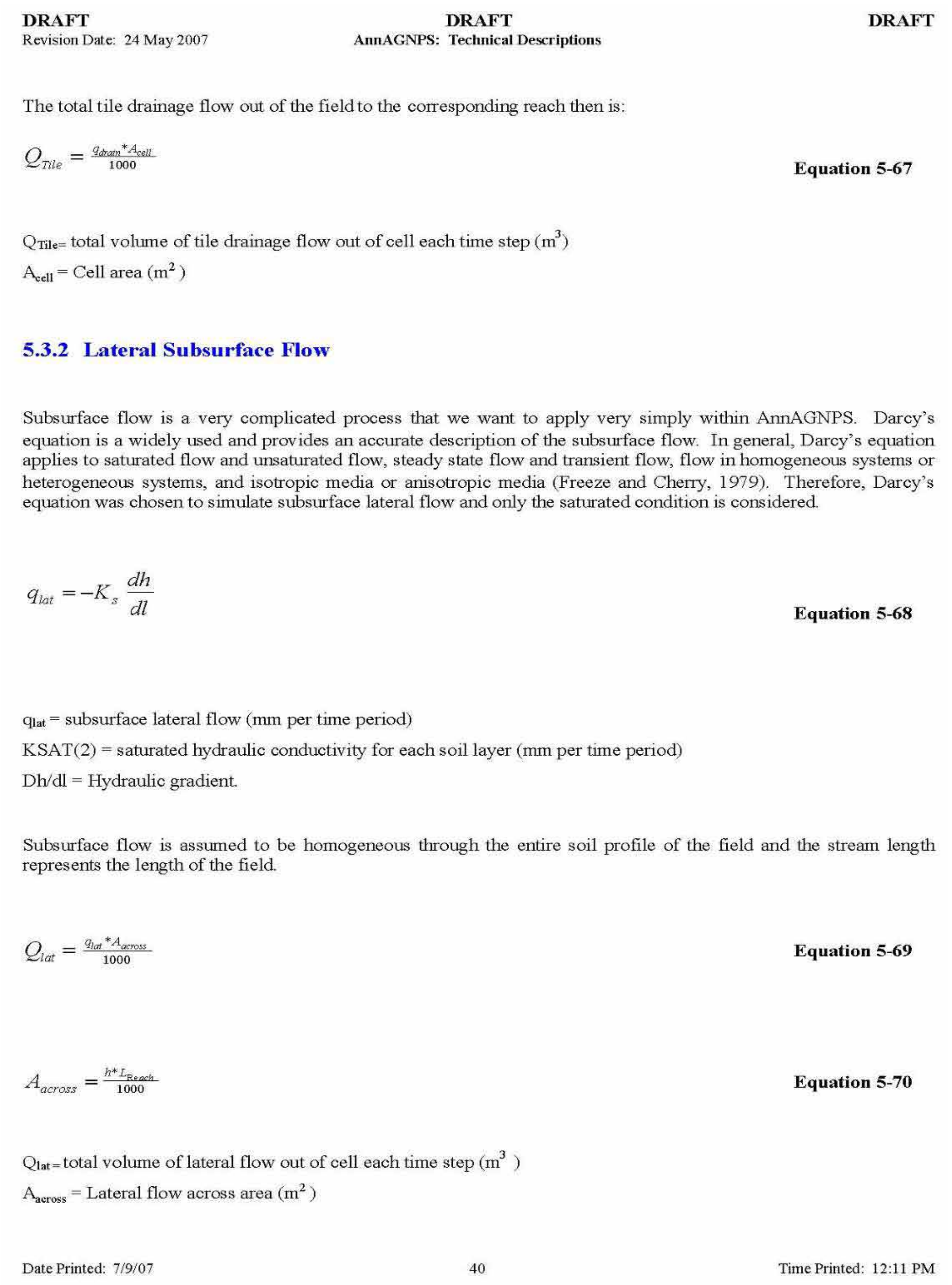
End of File

End Data

APPENDIX F

SUBSURFACE FLOW IN AnnAGNPS

(Extracted from AnnAGNPS Technical Processes (2007))



DRAFT **DRAFT** **DRAFT**

Revision Date: 24 May 2007 **AnnAGNPS: Technical Descriptions**

The total tile drainage flow out of the field to the corresponding reach then is:

$$Q_{Tile} = \frac{q_{drain} * A_{cell}}{1000}$$ **Equation 5-67**

Q_{Tile}= total volume of tile drainage flow out of cell each time step (m^3)

A_{cell} = Cell area (m^2)

5.3.2 Lateral Subsurface Flow

Subsurface flow is a very complicated process that we want to apply very simply within AnnAGNPS. Darcy's equation is a widely used and provides an accurate description of the subsurface flow. In general, Darcy's equation applies to saturated flow and unsaturated flow, steady state flow and transient flow, flow in homogeneous systems or heterogeneous systems, and isotropic media or anisotropic media (Freeze and Cherry, 1979). Therefore, Darcy's equation was chosen to simulate subsurface lateral flow and only the saturated condition is considered.

$$q_{lat} = -K_s \frac{dh}{dl}$$ **Equation 5-68**

q_{lat} = subsurface lateral flow (mm per time period)

KSAT(2) = saturated hydraulic conductivity for each soil layer (mm per time period)

Dh/dl = Hydraulic gradient.

Subsurface flow is assumed to be homogeneous through the entire soil profile of the field and the stream length represents the length of the field.

$$Q_{lat} = \frac{q_{lat} * A_{across}}{1000}$$ **Equation 5-69**

$$A_{across} = \frac{h * L_{Reach}}{1000}$$ **Equation 5-70**

Q_{lat}= total volume of lateral flow out of cell each time step (m^3)

A_{across} = Lateral flow across area (m^2)

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$$d_e = \frac{L_D \pi}{8[\ln(\frac{L_D}{r}) - 1.15]}$$

Equation 5-64

The depth of saturation above the impervious layer, h, is important to determine if there is flow into the tile drains. This requires keeping track of the soil moisture. For the top soil layer, the soil moisture is calculated as described previously. For the second soil layer, soil moisture is calculated as:

$$SM_{t+1} = SM_t + \frac{WI_t - PERC_t - ET_t}{Z}$$

Equation 5-65

If the soil moisture does not exceed the field capacity then there is no subsurface flow into the tile drains and the soil moisture is recalculated for next time step.

Otherwise, depth of saturation above the impervious layer is calculated as:

$$h = \frac{(SM_{t+1} - FC) * Z}{(PO - FC)}$$

Equation 5-66

where PO is the porosity of the soil layer

When the water table, h, is determined to be above the depth of drainage system, then the tile drainage rate is used based on the following conditions provided by the user:

a). If pipe spacing, pipe depth, depth to imperious layer and pipe diameter are supplied by user, then Hooghougt's equation is used in calculating drainage flow.

b). If pipe spacing, pipe depth, depth to imperious layer are supplied, Equation 5-61 is used and effective depth is assumed the same as the depth to the imperious layer.

c). If none of the above parameters are supplied by user and the user supplies the drainage rate (mm/hr), then the user supplied drainage rate is used.

d). If none of the parameters are supplied by user, based on practical USDA-NRCS design recommendation, then a value of 12.7 mm/day is used for the drainage rate. Therefore, 0.53 mm/hr or 1.6 mm for each three hours was used for AnnAGNPS.

Hooghoudt used the result of both of these observations to model the practical case of flow in drains. Hooghoudt's equation was originally developed for application in the Netherlands, where steady state rainfall is a reasonable assumption. The following is the Hooghoudt equation:

$$q_{drain} = \frac{8K_s d_e m + 4K_s m^2}{L_D^{\ 2}}$$ **Equation 5-61**

where q_{drain} = drainage flux (mm per time period),

K = saturated lateral hydraulic conductivity (mm per time period),

L_D = distance between drains (m),

m = midpoint water table height above the drain (m),

d_e = equivalent depth of the impermeable layer below the drain (m).

the effective depth, d_e is computed using Equations 5-62 and 5-63 when the actual depth, d, to the impermeable layer is such that $0 < d/L_D < 0.3$ (Skaggs, 1980).

$$d_e = \frac{d}{1 + \frac{d}{L_D}\left[\frac{8}{\pi}\ln(\frac{d}{r}) - \alpha_c\right]}$$ **Equation 5-62**

r = radius of the drain tube (m)

α_c = a constant defined by:

$$\alpha_c = 3.55 - \frac{1.6d}{L_D} + 2(\frac{d}{L_D})^2$$ **Equation 5-63**

For $d/L_D > 0.3$, d_e can be computing using Equation 5.64 (Skaggs, 1980).

The hydraulic gradient can be approximated by the local surface topographic slope, tanα which was used by the TOPMODEL (Beven et al., 1995). Ks can be estimated using the same method as percolation, soil profile is assumed as isotropic.

5.3.1 Tile Drainage Flow

Subsurface drainage by means of buried pipes has been studied very comprehensive in land drainage. The flow can be described as steady state or unsteady state flow. The steady state flow is based on the assumption that a steady constant flow occurs through the soil to the drains. Discharge equals recharge and the head is also constant. In the non-steady state formula all these parameters vary in time (Smedema and Rycroft, 1983). In most cases, subsurface drainage flow can be estimated based on steady state conditions. Hooghoudt's equation is chosen for use within AnnAGNPS because this formula has a wide applicability and a relatively simple structure (Smedema and Rycroft, 1983) and is also commonly used by the USDA-NRCS.

The water table above parallel drains is often approximated using an elliptical shape, as shown in Figure 5-1. The streamlines for the drainage flow towards two parallel pipes typically show a pattern as in Figure 5-1. Horizontal flow occurs towards the drains and the flow converges radially into the drain towards the end of its path. The extent of two flow zones differs from case to case depending particularly upon the relative magnitude of L, m and d. When L is large in comparison of both m and d, the flow is predominantly horizontal. An extensive radial flow sector is to be expected when d is large (van Schilfgaarde, 1957).

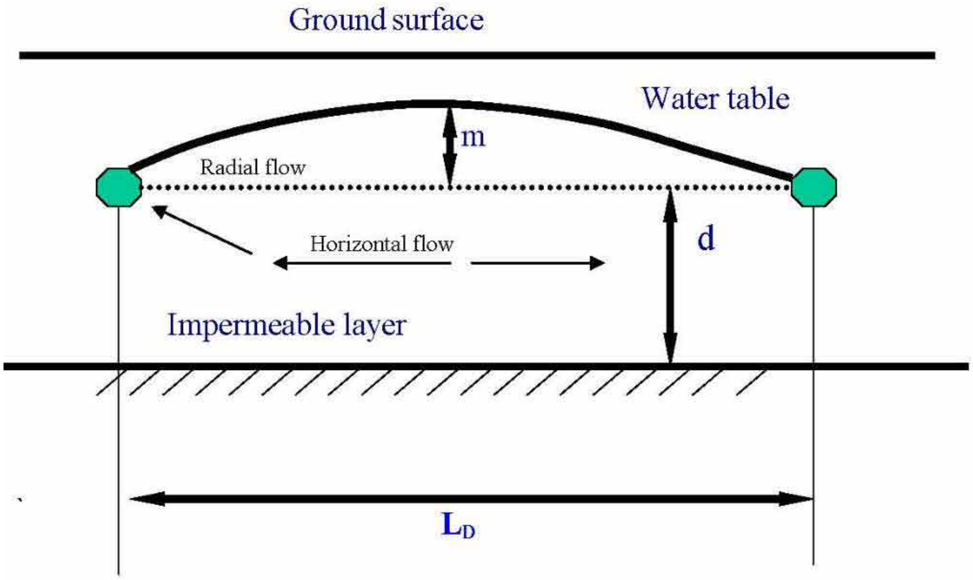

Figure 5-1. Schematic for Houghoudt Tile Flow

$$\gamma = 6.6X10^{-4}\left(101 - 0.0115Z + 5.44X10^{-7} Z_e^{\ 2}\right)$$ **Equation 5-58**

where the quantity in parentheses is an estimate of barometric pressure and is a function of elevation, Z_e (m). This quantity is described previously as part of the soil moisture calculations. This is stored as a constant parameter, as it does not vary with time.

The soil heat flux is calculated as a function of the air temperature for the current day and the three previous days:

$$G = 0.12\left[T_0 - \left(\frac{T_{-1} + T_{-2} + T_{-3}}{3}\right)\right]$$ **Equation 5-59**

where T_0 is the current day's temperature, and the other subscripts on T refer to the number of days prior to the current day. (This term is ignored in WEPP.)

The wind function appears in different forms in the WEPP and EPIC models and in the literature. Part of the differences are due to different assumed heights at which the wind speed is valid, and part of the difference is whether the function has already been divided by H_v (which must be some sort of average value, as it actually varies as a function of air temperature). In the United States, the standard height for measurement of wind speed at first-order weather observation stations is approximately 3 m, but in fact, strict adherence to this standard is not practiced, so that these measurements are taken anywhere from 2 m to 10 m (J. Marron, personal communication, 1996). The WEPP and EPIC models use equations valid for a 10 m height, with the justification that this is what the stochastic climate generator model (CLIGEN) produces. In light of these uncertainties, it was decided simply to use the original Penman wind function, which is valid for a height of 2 m (Jensen et al., 1990):

$$W = 6.43 + 3.4079U$$ **Equation 5-60**

where

U = wind speed (m/s)

With this, all terms are now available to calculate the potential evapotranspiration with the volume calculated based on the area of the field.

5.3 SUBSURFACE FLOW

The components of subsurface flow within AnnAGNPS consist of lateral subsurface flow or tile drain flow. Each are used to determine the contribution of subsurface drainage within a field to the corresponding reach. Subsurface flow only occurs within AnnAGNPS when an impervious layer is present within the soil profile. Amount of lateral flow and tile flow taken out from each cell is added to the reach the same time as runoff (no lateral flow and drainage flow between cells) and both are considered as the quick return flow to the reach. When the water table does not rise above the depth of drainage system, lateral flow is calculated using Darcy's equation as described for lateral subsurface flow.

h = Saturated depth from the imperious layer (mm)

L_{reach} = Reach length (m)

5.4 Channel Hydraulics and Hydrology

The description of the channels provides information to AnnAGNPS that is used to calculate in-stream and in-cell concentrated flows. This information is critical when sediment transport algorithms are used to determine the sediment yield within any location of the watershed. The following sections describe the methods used to determine the flow characteristics within channels.

5.4.1 Channel Hydraulics

The purpose of this channel hydraulics section is to describe the hydraulic geometry requirements, their options & defaults, and the algorithms necessary to solve for the flow depths, discharges, & velocities for both the in-cell & the in-stream transport processes within AnnAGNPS. Optional hydraulic geometry's, defaults, & values will also be described.

The general geometric shape for the in-cell concentrated flow channel cross-section is a trapezoid, since a trapezoid can be used as either a rectangle or a triangle by simply setting the proper parameter to zero; W = 0 for a triangle, or Z = 0 for a rectangle.

Whenever the geomorphic parameters for the cross-section are given, the depth is always interpreted to be:

1. for in-cell channel flow--hydraulic depth at the 2-year frequency; i.e., the 2-year frequency flow area divided by the top width for this same flow area; and
2. for in-stream channel flow--hydraulic depth at bankfull; i.e., the bankfull flow area divided by the top width for this same flow area.

The default Manning's roughness for the concentrated flow channel (n_{ch}) is the overland flow Manning's roughness (n_{ov}) value. The default slope (S_0) is the average land slope for the cell (S_{ov}). The ultimate default for the in-cell channel total length (L) is the standard power curve formula using the universal coefficient & exponent from Leopold et al (1964) corrected for units.

The preferred option is to give the cell channel segment length. The next preferred option is the total channel length from the hydraulically most distant point. The final option is to use the geomorphic parameters provided with the standard power curve formula. If all of the length fields are blank, the default in-stream channel total length is to be calculated by the standard power curve formula using the universal coefficient & exponent from Leopold et al (1964) corrected for units.

The compound in-stream cross-section shape assumes a rectangular main channel and a rectangle out-of-bank (floodplain) flow section. Provision is made for direct input of the basic shape parameters or for the use of geomorphic power curve functions. When out-of-bank flow is not desired, assume the average valley width is equal to the channel top width.

5.4.1.1 In-Cell Concentrated Flow

A key assumption used in the derivation for the following hydraulic equations is that the wetted perimeter is equal to the top width. This assumption greatly simplifies their solution without sacrificing any significant accuracy.

Figure 5-2 is a diagram of the trapezoidal cross-section dimensions used to define the generalized in-cell concentrated flow channel hydraulic geometry.

APPENDIX G

NITROGEN AND PHOSPHORUS IN AnnAGNPS

(extracted from AnnAGNPS Technical Processes (2007))

$$flow = \exp(-1.77 * Psp - 7.05)$$ **Equation 10-48**

Where:

flow = soil type-dependent P flow coefficient for soil layer on current day (dimensionless) (Sharpley and Williams, 1990; Jones, et al., 1984). It can be estimated based on following equations:

The value of aspr is restricted based on value of active P and stable P pools, and sign of aspr.

1). If aspr is positive sign and aspr is greater than start_actP, then set aspr equal to start_actP

$$aspr = start\_actP$$ **Equation 10-49**

2). If aspr is negatibe and the absolute value of aspr is great than start_stbP, then set aspr equal to minus start_stbP.

$$aspr = (-1) * start\_stbP$$ **Equation 10-50**

Compute new values for labile, active and stable P in soil layer 1 and 2 in ppm

a). Portion of incorporated inorganic P is added into labile P pool

$$labP = start\_labP - mpr + \frac{Psp * mnaP * 1000000}{conv}$$ **Equation 10-51**

Where:

labP = Amount of labile pool inorganic phosphorus in the composite cell's soil layer. Top layer is the first layer (g/Mg)

start_labP = starting day's soil layers' labile pool of inorganic phosphorous

$$Psp = 0.0045 * start\_labP - 5.3 * orgC + 0.39$$ **Equation 10-44**

3. for all the other cases:

$$Psp = 0.0043 * sat + 0.0034 * start\_labP + 0.11 * PH - 0.7$$ **Equation 10-45**

Psp has the limits of 0.05 and 0.75. Psp value is checked after calculations. If Psp is less than 0.05, 0.05 is set for this value; and if Psp is greater than 0.75, set Psp equals to 0.75.

Where:

Frac_caly = fraction of clay content,

Sat = base saturation (%),

PH = PH value,

orgC = Organic carbon content (%),

Calculation of flow rate between active P and stable P

Flow rate of P between active and stable are calculated as follow:

$$aspr = flow * (4 * start\_actP - start\_stbP)$$ **Equation 10-46**

1. When soil PH value is greater than 7.8 or the concentration of $CaCO_3$ is greater than zero.

The soil type dependent P flow coefficient is:

$$flow = 0.00076$$ **Equation 10-47**

Otherwise, the soil type dependent P flow coefficient is calculated as

Psp = P absorption coefficient for soil layer on current day (dimensionless) (Sharpley and Williams, 1990)

The actual value of mpr is restricted to the sign of mpr, values of labile and active pools. Positive sign implies flow from labile to active pool, negative sigh implies the opposite direction. The daily amount of P computed with above equation flows to the active mineral P and is, therefore, added to that pool and subtracted from the labile pool. To prevent oscillation of active and labile pools, only allow no more than half the difference between active and labile pools to move.

P sorption coefficient is defined as the fraction of fertilizer P remaining in the labile pool after the initial rapid phase of P sorption is complete. The P sorption coefficient is a function of chemical and physical soil properties as described by the following equations (Jones et al., 1984).

1. When soil PH value is greater than 7.8 or the concentration of $CaCO_3$ is greater than zero.

P sorption coefficient is calculated as

$$Psp = 0.58 - 0.61 * CaCO_3 \qquad \text{Equation 10-42}$$

Where:

Psp = P absorption coefficient for soil layer
$CaCO_3$ = Concentration of $CaCO_3$ (fraction).

The same as EPIC. However, in EPIC, $CaCO_3$ is in percent, so 0.0061 is used in above equation.

2. When soil PH value is less than 5.0 or base saturation is less than 35,

For clay content is greater than zero to prevent log zero

$$Psp = -0.047 * \ln(frac\_clay * 100) + 0.0045 * start\_labP - 5.3 * orgC + 0.39 \qquad \text{Equation 10-43}$$

For clay content is zero

$$mnaP = mnaP + \inf\_sol\_P$$ **Equation 10-39**

$$surf\_inorgP = surf\_inorgP - \inf\_sol\_P$$ **Equation 10-40**

If the infiltration is less than 1.0 mm, surface inorganic P remains in place.

10.2.3.2 Calculation of intermediate inorganic P mass balance

The intermediate inorganic P mass balance refers to P pools which includes P additions but prior to P losses as soluble P, sediment P, and plant uptake. Inorganic P added from manures or other fertilizers goes initially to the labile P pool and the active P pool, based on value of the P sorption coefficient. Units in following equation are ppm.

Calculation of flow rate between labile P and active P

Many studies have shown that after an application of inorganic P fertilizer, solution P concentration decreases rapidly with time due to reaction with the soil. This initial "fast" reaction is followed by a much slower decrease in solution P that may continue for several years (Barrow and Shaw, 1975; Munns and Fox, 1976; Rajan and Fox, 1972; Sharpley, 1982).

Equilibration between the solution and active mineral pool is governed by following equation:

Flow between labile P pool and active pool occurs only when soil temperature is above zero. It is calculated as:

$$mpr = 0.1 * \frac{SW}{f} * \exp(0.115 * T_{soil} - 2.88) * (start\_labP - start\_actP * \frac{Psp}{1 - Psp})$$ **Equation 10-41**

Where:

mpr = flow rate of P between labile and active P pools for soil layer on current day (+ implies flow from labile to active pool, - in opposite direction) (g/Mg/d) (Sharpley and Williams, 1990).

start_labP = starting day's soil layers' labile pool of inorganic phosphorous (ppm)

start_actP = starting day's soil layers' active pool of inorganic phosphorous (ppm)

inf_sol_P = mass of inorganic P infiltrated into soil layer from fertilizer applied on soil surface during rainfall event. (kg) ,

D = Thickness for soil layer (mm),

Q = runoff volume (mm),

Inf = amount of infiltration (mm).

Then, AGNPS resets mnaP and surf_inorg P values to reflect the impact of current rainfall event.

$$mnaP = mnaP + \inf\_sol\_P \qquad \textbf{Equation 10-35}$$

$$surf\_inorgP = 0 \qquad \textbf{Equation 10-36}$$

Case 2. When rainfall is not bigger enough to generate runoff, there is no loss to surface runoff. For this situation, AnnANPS assumes that inorganic P on the soil surface either stay in place or carried into soil profile with infiltration. The amount of surface inorganic P stay on soil surface or carried into soil profile with infiltration is determined as following:

If the infiltration is greater than 1.0 mm, the surface soluble inorganic P carried into soil profile with infiltration is calculated as:

$$\inf\_sol\_P = surf\_inorgP \qquad \textbf{Equation 10-37}$$

However, when the top soil layer is less than 200 mm, pro-rate lost to infiltration, which partition part of infiltration back to soil surface. This prevents mathematical problems later when the concentration is calculated based on the layer thickness.

$$\inf\_sol\_P = \frac{D}{200} * (\inf\_sol\_P) \qquad \textbf{Equation 10-38}$$

Then, AGNPS resets mnaP and surf_inorg P values to reflect the impact of current rainfall event.

If the infiltration is greater than 1.0 mm, the total soluble inorganic P lost to surface runoff is calculated as:

$$surf\_sol\_P = \frac{Q}{(Q + \inf)} * surf\_inorgP \qquad \textbf{Equation 10-29}$$

Inorganic P lost to infiltration is calculated as

$$\inf\_sol\_P = surf\_inorgP - surf\_sol\_P \qquad \textbf{Equation 10-30}$$

However, when the top soil layer is less than 200 mm, pro-rate the lost to infiltration, which partition part of lost to infiltration back to lost to surface runoff. This prevents mathematical problems later when the concentration is calculated based on the layer thickness.

$$surf\_sol\_P = surf\_sol\_P + (1.0 - \frac{D}{200}) * (\inf\_sol\_P) \qquad \textbf{Equation 10-31}$$

$$\inf\_sol\_P = \frac{D}{200} * (\inf\_sol\_P) \qquad \textbf{Equation 10-32}$$

If the infiltration is less than 1.0 mm, the total soluble inorganic P lost to surface runoff is calculated as:

$$surf\_sol\_P = surf\_inorgP \qquad \textbf{Equation 10-33}$$

$$\inf\_sol\_P = 0 \qquad \textbf{Equation 10-34}$$

Where:

surf_sol_P = mass of inorganic P in runoff from fertilizer applied on soil surface (kg), After a fertilizer application, the model updates the inorganic P mass balance.

a). When a soil disturbance exceeds 50 percent, for soils which the depth to imperious layer is greater or equal to 200 mm

$$mnaP = mnaP + inorgP\_applied$$ **Equation 10-25**

For soils which the depth to imperious layer is less than 200 mm:

$$mnaP = mnaP + \frac{D}{200} * inorgP\_applied$$ **Equation 10-26**

$$surf\_inorgP = surf\_inorgP + (1 - \frac{D}{200}) * inorgP\_applied$$ **Equation 10-27**

b). When a soil disturbance is less than 50 percent:

$$surf\_inorgP = surf\_inorgP + inorgP\_applied$$ **Equation 10-28**

Additions added to soil profile from rainfall processes

When rainfall occurs, it dissolves the inorganic P on the soil surface.

Case 1. When the rainfall event is bigger enough to generate runoff, runoff carries the dissolved inorganic P away from the field. In this situation, AnnANPS assumes that inorganic P on the soil surface is totally dissolved in the water and either carried away with runoff or carried into soil profile with infiltration. The amount of dissolved inorganic P carried away with runoff or carried into soil profile with infiltration is determined as following:

Where:

mnaP = mass of inorganic P added to a cell from incorporated inorganic additions such as fertilizers (kg). It is assumed well mixed with soil.

surf_inorgP = surface inorganic phosphate for a cell, added through fertilization at the soil surface (kg).

Otherwise, if the soil depth to imperious layer is less than 200 mm (not many this kind of cases), to prevent the concentration of fertilizer in the top layer to skyrocket, AnnAGNPS incorporates only the pre-rated fraction of fertilizer application into the top soil layer. For this case,

$$mnaP = \frac{D}{200} * surf\_inorgP \qquad \textbf{Equation 10-22}$$

$$surf\_inorgP = surf\_inorgP - mnaP \qquad \textbf{Equation 10-23}$$

D is the depth to the impervious layer and it is less than 200 mm for this case.

Fertilizer inorganic P added to a cell

Inorganic P from fertilizer application is calculated using the rate of fertilizer applied for current day operation times the fertilizer inorganic P fraction (from fertilizer reference database weight/weight).

$$inorgP\_applied = (fer\_app) * (frac\_inorgP) * A_{cell} \qquad \textbf{Equation 10-24}$$

Where:

inorgP _applied = inorganic P from fertilizer application on current day (kg)

fer_app = the rate of fertilizer applied for current day operation (kg/ha)

frac_inorgP = fertilizer inorganic P fraction, from fertilizer reference database (Weight/Weight).

other fertilizers goes initially to the labile P (available for plant use) pool and the active P pool, based on value of the P sorption coefficient. Fertilizer P which is labile at application may be quickly transferred to the active mineral pool. Flow between the active and stable mineral pools is governed by a P flow rate.

Within each inorganic P pool, additions from fertilizer application, mineralization of organic P is calculated first, followed by the losses from runoff, sediment and plant uptake. At the end of the day, mass balance was updated for each P pool. The simulation is in a sequence of calculation.

10.2.3.1 Calculation of inorganic P additions to a cell

Added fertilizers are considered either well mixed with the top soil layer which is 200 mm or stay on soil surface based on the operation effect which is supplied by the user through operation data section. If a soil disturbance exceeds 50 percent, any fertilizer operations are considered as mixed. Otherwise, it assumes the applied fertilizer stays on soil surface. In addition, when the soil disturbance exceeds 50 percent, it not only incorporates the applied fertilizer from current operation into soil, but also incorporates any fertilizer left on the soil surface from previous fertilization into soil.

When a soil disturbance exceeds 50 percent, fertilizers on soil surface mix with soil. The amount of fertilizer mixed with soil and the amount of fertilizer left on the soil surface after a soil disturbance is determined by the depth to the impervious layer. If the soil depth to imperious layer is greater than 200 mm (AnnAGNPS set this layer as the top soil layer, it is also called tillage layer), take all surface fertilizer and incorporate it into soil. For this case:

$$mnaP = surf\_inorgP$$ **Equation 10-20**

$$surf\_inorgP = 0$$ **Equation 10-21**

$$frac\_orgP\_clay = \frac{orgP}{(frac\_clay)*1000000} \qquad \text{Equation 10-18}$$

Where:

orgP = Concentration of organic_P in the total composite soil layer (1) for current day (ppm)

frac_clay = Ratio of clay mass to sum total mass of mineral soil (sand, silt, clay) excluding rock in the soil layer.

Organic P mass balance is maintained for the second soil layer which is the bottom soil layer. For second soil layer, there is not much to talk about because AnnAGNPS assumes that fertilizer application, rainfall caused runoff and sediment loss are only associated with the top soil layer. In other word, fertilizer application, rainfall does not interact in the bottom soil layer.

$$orgP_t = orgP_{t-1} - \frac{hmnP*1000000}{conv} \qquad \text{Equation 10-19}$$

Where:

$orgP_t$ = Concentration of organic_P in the total composite soil layer (for current day(ppm)

$orgP_{t-1}$= Concentration of organic_P in the total composite soil layer for previous day(ppm)

hmnP = P mineralized from organic P in soil layer on current day (actual argument passed to inorg_P_mass_bal subroutine (kg). The calculation of P mineralized is the same as the first layer.

10.2.3 Inorganic P Simulation Processes

AnnAGNPS monitors three different pools of inorganic phosphorus in the soil as mentioned before. It adapts the mineral P model developed by Jones et al (1984). Mineral P is transferred among three forms: labile P in solution (available for plant use), the active P and stable P. AnnAGNPS assumes that inorganic P added from manures or

$$F_w = \frac{SW}{f}$$ **Equation 10-15**

Where:

SW= the water content of soil layer on a given day (mm H2O)

f = the water content at saturation (mm H2O)

T_{soil} = the average cell soil temperature (°C).

The correction factor (corr) is calculated as:

$$corr = sqrt(F_t * F_w)$$ **Equation 10-16**

10.2.2.4 Calculation of mass of P attached to sediment

Assumption:

The organic phosphate is associated with clay fraction. This eliminates the need for separate nutrient enrichment ratio (Menzel; 1980 from GLEAM documentation).

cell_sed_P is in kg, cell_sed_part is metric tons, so multiply by 1000.

$$sed\_orgP = frac\_orgP\_clay * (sed\_part(1,1) + sed\_part(1,2)) * 1000$$ **Equation 10-17**

Where:

sed_orgP = mass of phosphorus attached to sediment (kg). Sed_part is metric tons, so multiply by 1000.

frac_ orgP_clay = decimal fraction of organic P in clay in soil layer (g/g)

sed_part(1,1) and sed_part(1,2) = Current day's mass of sediment (by particle size and source) at edge of cell. Array subscript are: Particle Size (first): 1 - clay 2 - silt 3 - sand 4 - small aggregate 5 - large aggregate Source (second): 1 - irrigation 2 - other than irrigation.

Frac_actP = fraction of active P,

orgP = amount of organic P in the cell soil composite layers (g/Mg)

corr = correction factor which computes moisture/temperature correction used in N and P mineralization equations (From EPIC, Sharpley and Williams,1990) non-dimensional

The tillage impact on mineralization is not considered in AnnAGNPS. In this way, it reduces the need for calculating the ratio of bulk density to settled bulk density. In addition, conservation tillage such as no-tillage as recommended by the NRCS, the ratio of bulk density to settled bulk density is one.

The way to calculate the fraction of active P pool in AnnAGNPS is different from SWAT. The fraction is calculated based on the cultivation history.

The active pool fraction is calculated based on following equation:

$$frac = 0.4 * \exp(-0.0277 * YC) + 0.1$$ **Equation 10-12**

Where YC is the period of cultivation before the simulation starts (year), the concepts expressed in above equation are based on work of Hobbs and Thompson (1971). For crop land, year of cultivation is set to 50, otherwise, it is set to zero. Below the plow layer, the active pool fraction is set to 40% of plow layer value. This is based on work of Cassman and Munns (1980).

The water, temperature correction factor varies between 0 to 1.0. The calculation of correction factor is based on the temperature correction factor (F_t) and water correction factor (F_w). It is calculated the same way as in EPIC. The temperature correction factor (F_t) for P mineralization is calculated based on following equations:

$$F_t = \frac{T_l}{T_l + \exp(9.93 - 0.312 * T_l)} \qquad 0 < T_l < 100$$ **Equation 10-13**

$$F_t = 0 \qquad T_l <= 0$$

In order to ensure temperature correction does not fall below 0.1,

$$F_t = MAX(F_t, 0.1)$$ **Equation 10-14**

Water correction factor (F_w) for P mineralization is calculated as

$$fer\_orgP = (fer\_app) * (frac\_orgP) * A_{cell}$$ **Equation 10-10**

Where:

fer_orgP = organic P from fertilizer application on current day (kg)

fer_app = the rate of fertilizer applied for current day operation (kg/ha)

frac_orgP = fertilizer fraction which is organic P, from fertilizer reference database (Weight/Weight)

10.2.2.3 Mineralized P from organic P on current day

Mineralization is a microbial process which converts organic, plant unavailable phosphorus to inorganic, plant-available phosphorus (phosphate). Immobilization is the microbial conversion of plant-available inorganic soil phosphorus to plant unavailable organic phosphorus. In the United States, approximately 4 to 22 lb P_2O_5/acre has been generated by phosphorus mineralization each year (Jones and Jacobsen, 2002). Jones and Jacobsen (2002) also reported that: "Mineralization occurs most readily when the C:P ratio is less than 200:1, and immobilization occurs when that ratio is greater than 300:1". Temperature, soil moisture, aeration, and PH affect phosphorus mineralization as they affect the N Mineralization (Sharpley and Williams, 1990). The phosphorus mineralization algorithms in AnnAGNPS are net mineralization algorithms which incorporate immobilization into the equations.

The P mineralization equation in AGNPS is adapted from the EPIC model (Sharpley and Williams, 1990). This epic mineralization model is similar in structure to the N mineralization model developed by Jones et al. (1984). Mineralization and decomposition are dependent on water availability and temperature. Mineralization from the fresh organic p pool associated with crop residue and microbial biomass is estimated for each soil layer with the equation.

$$hmnP = CMN * frac * orgP * corr * \frac{conv}{1000000}$$ **Equation 10-11**

Where:

hmnP = the mineralization rate (kg/ha/d) from the humus active organic P pool in soil layer. It is the P mineralized from active organic P in soil layer on current day (actual argument passed to inorg_P_mass_bal subroutine (kg/d)

CMN = The humus rate constant, in EPIC it is approximately 0.0003 (d^{-1}), hard-coded to 0.016 (see init_parm subroutine))

CPR is assumed 3000 for grassland (which means the Carbon to Phosphorus ratio in dry biomass is 3000), 1500 for forest systems, and zero for urban or mixed land.

(Hingston and Raison, 1982; Odum, 1971; Prescott, et al, 1989)

c. Subsurface residue P calculation for non-crop land

$$res\_subsP = \frac{(Res\_decomp) * 0.5}{CPR}$$ **Equation 10-8**

Where:

res_subsP = noncrop organic P addition from decomposed subsurface (below ground) residue (kg),

CPR = Carbon to Phosphorus ratio for dry total biomass for noncrop fields (weight of carbon/weight of Phosphorus),

res_decomp = crop residue mass decomposition for current day (kg).

$$res\_decomp = (sub\_res) * (1 - \exp(-temp\_f * (nonc\_decomp\_coeff))) * A_{cell}$$ **Equation 10-9**

Where:

sub_res = noncrop subsurface residue for a cell which is computed from RUSLE module (kg/ha)

temp_f = RUSLE temperature correction factor for noncrop subsurface residue decomposition.

nonc_decomp_coeff = noncrop surface residue decompsition coefficient (nonc_decomp_coeff is hard-coded to 0.016.

10.2.2.2 Cell organic P from fertilizer application

Cell organic P from fertilizer application is calculated using the rate of fertilizer applied for current day operation times the fertilizer fraction which is organic P (from fertilizer reference database weight/weight).

Where:

T_{soil} = the average cell soil temperature (°C).

Above equation is a simplification of temperature correction factor from RUSLE (Page 152, equation 5-7). The 32.0 in temp_f equation is the RUSLE (To) value (°C) which is 90 (°F), and the 8.0 is the A value, in deg. C. The equation assumes residue, irrespective of crop, is 50% organic carbon. The detail of this part is described in the cell residue calculation document.

b. Non-crop land

For non-crop land, both surface layer and subsurface layer were considered for decomposition.

For surface layer

The cell residue P is calculated using following equations:

$$resP = \frac{(\mathrm{Re}s\_decomp) * 0.5}{CPR}$$ **Equation 10-6**

Where:

resP = organic P addition from decomposition of noncrop residue (kg).

CPR = Carbon to Phosphorus ratio for dry total biomass for noncrop fields (weight of carbon/weight of Phosphorus).

res_decomp = noncrop residue mass decomposition for current day (kg).

$$res\_decomp = (surf\_res) * (1 - \exp(-temp\_f * (nonc\_decomp\_coeff))) * A_{cell}$$ **Equation 10-7**

Where:

surf_res = surface residue for a cell which is computed from RUSLE module (kg/ha)

temp_f = RUSLE temperature correction factor, for noncrop res decomp, used to adjust the calculation of residue decomposition based on a first order rate, constant (unitless)

nonc_decomp_coeff = noncrop surface residue decompsition coefficient (nonc_decomp_coeff is

The cell residue P is calculated using following equations:

$$resP = \frac{(res\_decomp) * 0.5}{CPR_{harvest}}$$ **Equation 10-3**

Where:

resP = organic P addition from decomposition of crop residue laying on the soil surface on current day (kg)

res_decomp = crop residue mass decomposition for current day (kg)

$CPR_{harvest}$ = Ratio of Carbon to phosphorus for crop at harvest

$$res\_decomp = (surf\_res) * (1 - \exp(-temp\_f * (decomp\_coeff))) * A_{cell}$$ **Equation 10-4**

Where:

surf_res = surface residue for a cell which is computed from RUSLE module (kg/ha)

temp_f = RUSLE temperature correction factor (unitless)

decomp_coeff = crop surface residue decomposition coefficient, user input, the default value is 0.016.

Temperature correction factor is calculated using following equation:

$$temp\_f = \frac{3200 * ((T_{soil} + 8)**2) - (T_{soil} + 8)**4}{2560000} \qquad 0 < T_{soil} < 32$$

$$temp\_f = 1$$ **Equation 10-5**

$$temp\_f = 0$$

conv = intensive unit to extensive unit conversion factor (kg)

D = thickness of soil layer (mm)

ρ_b = bulk density of composite soil layer (g/cc or Metric tons/ m^3)

A_{cell} = AnnAGNPS cell area (hectares)

10.2.2 Organic Phosphorus Simulation Processes

All AnnAGNPS mass balances were based on AnnAGNPS cells and maintained for two composite soil layers.

The mass balance equation for organic P simulation processes is as followings:

For Soil Layer 1

$$orgP_t = orgP_{t-1} - \frac{(resP + fer\_orgP - hmnP - sed\_orgP) * 1000000}{conv} \qquad \textbf{Equation 10-2}$$

Where:

$orgP_t$ = Concentration of organic_P in the total composite soil layer for current day (ppm)

$orgP_{t\text{-}1}$ = Concentration of organic_P in the total composite soil layer for previous day (ppm)

resP = organic P addition to cell soil layer 1 from decomposed fresh crop residue on current day (kg)

fer_orgP = organic P from fertilizer application such as manure or other sources (kg)

hmnP = The mineralization rate from the humus active organic P pool on current day (kg)

sed_orgP = current days mass of P attached to sediment (kg)

10.2.2.1 Cell Residue P Calculations

Decomposition is the breakdown of fresh organic residue into simpler organic components. It is calculated once a day. Equations for residue decomposition were adapted from RUSLE (Renard et al., 1997). The decomposition calculations are different from crop land to noncorp land. For crop land, only surface decomposition is calculated. For noncrop land, both surface decomposition and subsurface decomposition are calculated. Crop residue mass decomposition is not corrected for moisture, but is corrected for temperature by the factor temp_f.

a. Crop land

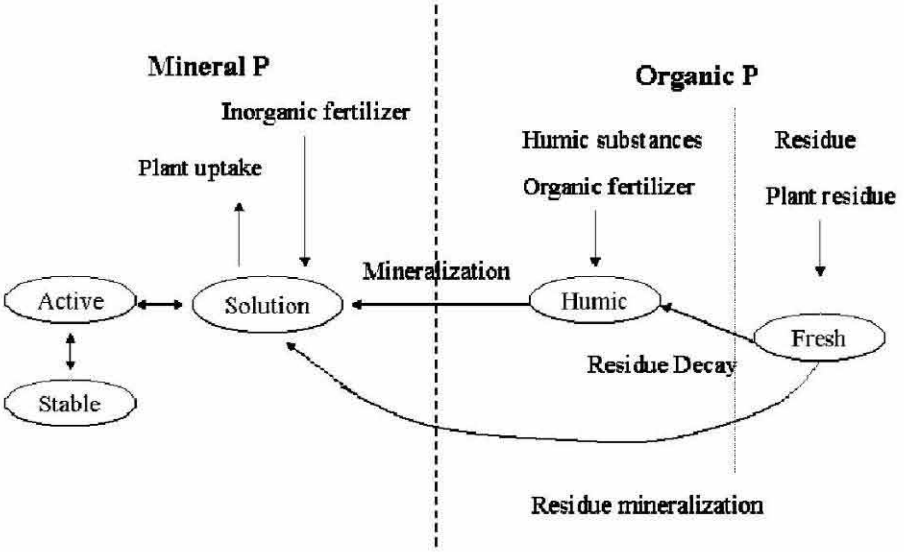

Figure 10-2. Processes simulated in AnnAGNPS

10.2.1 Soil Initial Phosphorus Contents and Conversion Factor

Users can define the amount of inorganic and organic P contained in soil layers. If such information is not available, users can use default values for inorganic and organic phosphorus concentration (mg/kg or ppm). The default value for organic P is assumed as 1.5% of the soil organic matter; and inorganic P is assumed as 0.75% of the soil organic matter (Stevenson, 1994). Soil organic matter is usually available from national soil database such as NASIS.

The input phosphorus levels in the soil profile are as concentrations, but AnnAGNPS performs calculations on a mass basis. To convert a concentration to a mass, AnnAGNPS uses a conversion factor (conv). Conversion factor represents a weight of soil in that it is a volume of soil times bulk density. It is used to convert nutrient concentration in soil to kilograms used to do mass balances.

The concentration of inorganic phosphorus and organic phosphorus in top soil layer is initially set to 500 mg/kg (ppm) soil, 250 mg/kg (ppm) soil in the bottom soil layer.

$$conv = D * 10 * 1000 * \rho_b * A_{cell}$$ **Equation 10-1**

Where:

Precipitation is the processes through which soluble P is converted to part of mineral. The solubility of P minerals controls the available P concentrations. Calcium phosphate is the dominant minerals in neutral to high PH soils. There are numerous forms of calcium phosphate in soil, ranging from very soluble to very insoluble. Usually, after fertilizing with P in a neutral or high PH soil, calcium phosphate forms in order from high to low solubility, and the time for each mineral to form is highly dependent on temperature (Jones and Jacobson, 2002).

Al phosphate and Fe phosphate are the dominant minerals in soils with PH levels below 6.5 (Havlin et al., 1999). Opposite to the calcium phosphate, the solubility of these minerals decreases at lower PH. Therefore, P is most available around PH 6.5 (Havlin et al., 1999).

10.2 ANNAGNPS PHOSPHORUS PROCESSES

The purpose of the P module in AnnAGNPS is to extract P into surface runoff and output it from a cell (a *transport* process). In doing so an appropriate soil mass balance of phosphorus (P) in a cell must be maintained on a daily basis by horizon or computational layer. It is not a detailed chemical model of P in the soil, but simulates the effect of P adsorption that control P availability and partitioning into runoff. The mass balance portion of the model is a simplification of the EPIC (Sharpley and Williams, 1990) P model (Sharpley, et al., 1984). In this model, P is partitioned into organic P and mineral P. Mineral P is further broken down into: 1) labile P (that P readily available for plant uptake, for example fertilizer P; 2) active mineral P (P that is more or less reversibly absorbed to the soil), and stable mineral P (absorbed P that is “fixed” or relatively irreversibly chemisorbed to the soil adsorption complex or as discrete insoluble P minerals). An empirical distribution coefficient, Kd, is used to partition P between the soluble and absorbed phases, thus dictating the amount of P available for extraction into runoff. Sediment-bound P is estimated from soil erosion and is assumed associated with the clay-size fraction of the soil and consists of the organic, active and stable mineral P. Figure 10-2 shows the P processes simulated in AGNPS

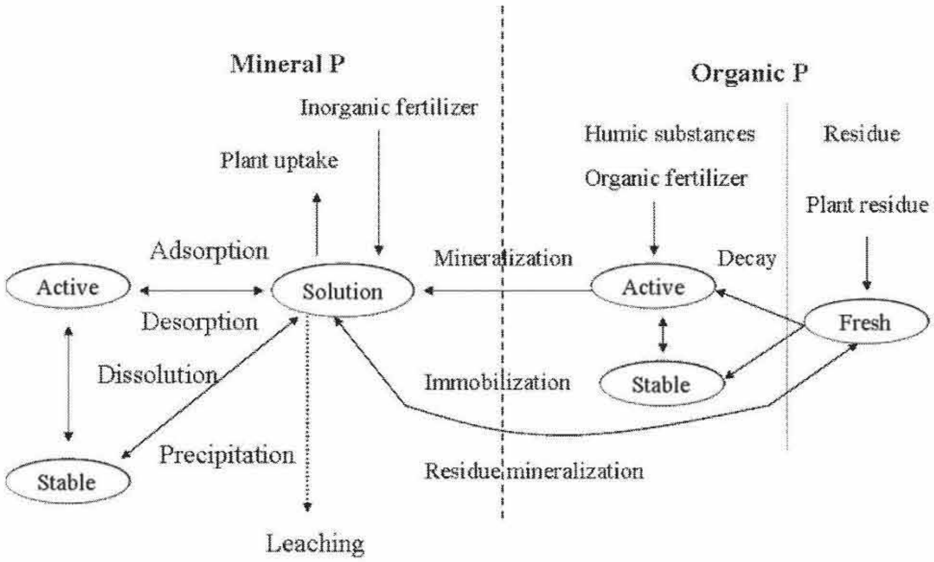

Figure 10-1. A simplification of phosphorus processes (Havlin et al., 1999)

Decomposition is the breakdown of fresh organic residue into simpler organic components. **Mineralization** is the microbial conversion of organic, plant unavailable phosphorus to inorganic, plant-available phosphorus. **Immobilization** is the microbial conversion of plant-available inorganic soil phosphorus to plant unavailable organic phosphorus (Figure 10-1). Approximately 4 to 22 lb P2O5/ac has been mineralized each year in the United States (Jones and Jacobson, 2002). The decomposition and mineralization processes is controlled by the decay rate constant which is a function of Carbon-Nitrogen (C: N) ratio (CNR) and Carbon- Phosphorus (C:P) ratio (CPR) in the residue, temperature, soil water content, PH values, cultivation intensity, P fertilization and composition of crop residue. Studies (Havlin et al., 1999) show that mineralization occurs most readily when the C:P ratio is less than 200:1, and immobilization occurs when that ratio is greater than 300:1. Mineralization is increased with the total organic P content. With continued cultivation, the P mineralization decreases because the organic P decrease.

Absorption refers to the binding of P to soil particles. Absorbed P is bound only to the outside of minerals. The solution P is usually in a form of HPO_4^{-2} or $H_2PO_4^{-}$, so it is strongly attached to positive charged minerals. Because minerals become more positively charged at lower PH, more phosphate is absorbed at lower soil PH values; whereas more phosphate is available for plant uptake at higher soil PH values (Havlin et al., 1999). In addition, as more P fertilizer is added, more P is available for plant uptake. P absorption is generally increased with increased temperature (Jones and Jacobson, 2002). **Desorption** is the opposite of absorption. Factors that affect absorption affect desorption too.

10. PHOSPHORUS

10.1 GENERAL INTRODUCTION

Phosphorus is an essential nutrient for all life forms and it is required for many essential functions. Research has shown that a deficiency of phosphorus in soils could limit crop production (Maples and Keogh, 1973). A deficiency of phosphorus in fresh water could limit production of fresh water organisms; wherea an abundance of phosphorus in fresh water will lead to algal blooms. Algae blooms have many detrimental effects on natural ecosystems. Odors and discoloration caused by decay of algae clumps will interfere with recreational and aesthetic water use; algae blooms shade submerged aquatic vegetation, reducing or eliminating photosynthesis and productivity; and algae may clog water treatment plant filters (Sharpley et al., 1994).

Phosphorus is not as mobile as nitrogen, it is generally strongly absorbed by soil. The phosphorus absorbed by sediment particles may be transported in overland flow. Orthophosphate can be dissolved in the water and be transported by surface and sub-surface flow (Smith, 1990). Sharpley and Syers (1979) observed that surface runoff is the primary mechanism by which phosphorus is exported from most catchments.

Agricultural conservation practices which control erosion and runoff will definitely control the load of phosphorus and orthophosphate to surface water bodies. However, reducing sediment transport will not reduce the phosphorus transport by the same magnitude.

10.1.1 Phosphorus Cycle

Phosphorus does not occur as abundantly as nitrogen in soil. Total P in surface soils ranges from 0.005% to 0.15% (Halvin et al., 1999). A complete understanding of the relationship and chemical, physical and biological interactions of various phosphorous forms in the soil profile is essential for a full description of phosphorous cycle in soils and plants (Jones et al, 1984). A model based on mathematical descriptions of fundamental chemical, physical and biological mechanisms of the soil phosphorus behavior would be ideal for phosphorous modeling. However, complex physiochemical mechanisms of phosphorus have not been fully described (Havlin et al., 1999). Therefore, all available phosphorus models are simplification of real world and are more empirical approach.

The general phosphorus processes in soil is illustrated in Figure 10-1. Generally, there are six forms (six pools) of phosphorus available in the soil profile. Of those six forms, three major forms of phosphorus in soils are organic phosphorus associated with humus (active and stable in organic pool), insoluble forms of mineral phosphorus (stable in inorganic pool), and plant-available phosphorus in soil solution (labile in solution). Phosphorus may be added to the soil by fertilizer, manure or residue application (both organic and inorganic). Phosphorus is removed from the soil by plant uptake, runoff, soil erosion and leaching. The pool of solution inorganic phosphorus supplies the plant, which can be divided into root, shoot and grain. The root and shoot (plant residue) or manure residue add to the fresh organic pool (Jones et al, 1984). Transformation of crop residue to other forms are very complicated and limited by many factors in soil. For soil inorganic phosphorus, the labile pool (solution) is in rapid (several days or week) equilibrium with the active pool; but the active pool is in slow equilibrium with the stable pool (Jones et al, 1984).

$$N\_Lateral\_Flow = \frac{Lateral\_flow}{SW(2) - Wilting(2)} * \frac{inorgN(2) * conv(2)}{1000000} \qquad Lateral\_flow > 0$$

$$N \quad Lateral \quad Flow = 0 \qquad\qquad Lateral\_flow <= 0$$

Equation 9-50

Where:

N_Lateral_Flow = amount of nitrogen lost to subsurface lateral flow on current day (kg),
Lateral_flow = amount of subsurface lateral flow out of the second soil layer on current day (mm),
SW (2)= soil water content of the second soil layer (mm),
Wilting (2) = wilting point of the second soil layer (mm),
inorgN (2) = amount of nitrate nitrogen in the second soil layer (ppm),
conv = conversion factor.

The total loss to subsurface flow is the sum of above two. At the end of the day, the inorganic nitrogen content shall be recalculated to reflect the losses to subsurface flow.

$inorgN_t$ = Concentration of inorganic_N in the total composite soil layer for current day (ppm)

Inorganic nitrogen mass balance is maintained for the second soil layer the same way as the top layer except that fertilizer application, rainfall caused runoff and sediment loss are not considered. The leaching from first layer is added to the second layer and leaching from second layer is lost to the groundwater system.

9.2.6 Losses to Subsurface Flow

Losses to subsurface flow is considered as two parts: loss to subsurface drainage flow (tile flow) and loss to subsurface lateral flow.

9.2.6.1 Calculation of inorganic N loss through subsurface drainage (tile drain) systems

Loss to subsurface drainage flow (tile flow) is calculated using the updated inorganic nitrogen level in the second soil layer.

$$N\_subsurface\_drain = \frac{drain\quad outflow}{SW(2) - Wilting(2)} * \frac{inorgN(2) * conv(2)}{1000000} \qquad drain\_outflow > 0$$

$$N\_subsurface\_drain = 0 \qquad drain\_outflow <= 0 \qquad \textbf{Equation 9-49}$$

Where:

N_subsurface_Drain = amount of nitrogen lost to subsurface drainage on current day (kg),
drain_outflow = amount of water drained through subsurface drainage system on current day (mm),
SW (2)= soil water content of the second soil layer (mm),
Wilting (2) = wilting point of the second soil layer (mm),
inorgN (2) = amount of nitrate nitrogen in the second soil layer (ppm),
conv = conversion factor.

9.2.6.2 Calculation of inorganic N loss to subsurface lateral flow

Loss to subsurface lateral flow is calculated as follow:

$$sol\_N = cell\_soil\_sol\_N + surf\_sol\_N$$ **Equation 9-46**

Where:

cell_soil_sol_N = nitrogen losses to runoff from composite soil layer (kg)
surf_sol_N = nitrogen losses to runoff from soil surface (kg)
sol_N = total mass of inorganic N lost in surface runoff.

9.2.5 Leaching

Leaching losses is calculated using the updated inorganic nitrogen level in the soil.

$$N\_Leaching = \frac{perc\_loss}{SW - Wilting} * \frac{inorgN * conv}{1000000} \qquad perc\_loss > 0$$ **Equation 9-47**

$$N\_Leaching = 0 \qquad perc\_loss <= 0$$

Where:

N_leaching = leaching loss from soil layer (kg),
Perc_loss = percolation loss for current day (mm)
SW = soil water content (mm),
Wilting = wilting point (mm),
inorgN = amount of nitrate nitrogen in the soil (ppm),
conv = conversion factor.

Then, the inorganic nitrogen content shall be recalculated to reflect the leaching losses at the end of the day.

$$inorgN_t = inorgN_{i+1} - \frac{(N\_Leaching) * 1000000}{conv}$$ **Equation 9-48**

Where:

Plant nitrogen uptake is adjusted based on the availability of nutrient in the soil. If uptN calculated above is greater than the available inorganic N in the soil layer, then a limited crop N uptake is calculated as:

$$\lim ited\_uptN = 0.99 * \frac{inorgN * conv}{1000000}$$ **Equation 9-44**

Where:

Limited_uptN = mass of inorganic nitrogen taken up by the plant on current day (kg/d),
inorgN = amount of nitrate nitrogen in the soil (ppm),
conv = conversion factor.

9.2.3.4 Reconcile inorganic N mass balance

Inorganic mass balance is updated. Mineralized N is added.

$$inorgN_{i+1} = inorgN_i + \frac{(hmnN - uptN - cell\_soil\_sol\_N - DN) * 1000000}{conv}$$ **Equation 9-45**

Where:

$inorgN_{i+1}$ = Concentration of inorganic_N in the total composite soil layer for current day (ppm)
$inorgN_i$ = Concentration of organic_N in the total composite soil layer for previous day(ppm)
hmnN = inorganic N mineralized from organic matter (kg). In the inorganic forms of nitrogen, it simulates amount of nitrogen generated through nitrogen mineralization on a daily basis.
uptN = from growth_stage subroutine. Call cell_growth stage subroutine to get this value.
cell_soil_sol_N = soil incorporated inorganic N lost to runoff, kilograms (kg)
DN = denitrification rate (kg),

9.2.4 Total Inorganic Nitrogen Losses to Surface Runoff

Total mass of inorganic N lost in surface runoff includes soil incorporated and surface applied N lost.

Denitrification occurs only when soil moisture content is above the 90% of porosity.

$$DN = \frac{inorgN * conv}{1000000} * (1 - \exp(-1.4 * F_t * orgC)) \qquad F_w > 0.9 \qquad \textbf{Equation 9-42}$$

$$DN = 0 \qquad F_w < 0.9$$

Where:

DN = denitrification rate (kg),

inorgN = amount of nitrate nitrogen in the soil (ppm),

conv = conversion factor,

F_t = nutrient cycling temperature factor, temperature correction factor as used for mineralization

orgC = organic carbon content (%)

F_w = nutrient cycling water factor, as used for mineralization

Loss through plant uptake of inorganic nitrogen

In AnnAGNPS, the amount of crop nutrient uptake is calculated in a crop growth stage subroutine. This subroutine determines the crop growth stage based on crop data a user supplied. Amount of nutrient uptake was calculated based on the crop growth stage. Four growth stages are simulated by AnnAGNPS. There are initial; development; mature; senescence. The length of each growth stage can be specified by a user or use the RUSLE (Renard et al., 1997) crop database information. At different growth stage, crop nutrient uptake is different. The crop nutrient uptake is also limited by available nutrients in the composite soil layer. The calculated crop uptake N in the crop growth stage subroutine passes to inorganic N mass balance. Nitrogen uptake on current day is calculated as follow:

$$uptN = \frac{growth\_N\_uptake * (yield\_wt) * N\_uptake\_harvest}{stage\_length} * A_{cell} \qquad \text{Equation 9-43}$$

Where:

uptN = mass of inorganic nitrogen taken up by the plant on current day (kg/d),

growth_N_uptake = Fraction of N uptake for current growth stage. Growth stages are initial, development, mature, and senescence,

yield_wt = yield at harvest (Kg/ha).

N_uptake_harvest = N uptake per yield unit at harvest (wt-N / wt-harvest unit, dimensionless)

stage length = the number of growing days for current growth stage (days).

9.2.3.2 Calculation of intermediate inorganic N mass balance

The intermediate inorganic N mass balance refers to N pools which includes N additions but prior to N losses as soluble N, sediment N, and plant uptake. Bottom soil layer inorganic N does not change with this operation.

$$inorgN_i = inorgN_{t-1} + \frac{mnaN * 1000000}{conv}$$ **Equation 9-40**

Where:

$inorgN_i$ = Intermediate concentration of organic_N in the total composite soil layer for current day (ppm)

$inorgN_{t-1}$ = Concentration of organic_N in the total composite soil layer for previous day (ppm)

mnaN = inorganic N addition to the soil profile. From above calculation (kg)

9.2.3.3 Calculation of inorganic N losses from a cell

This calculation will include sequential adjustments to N pool size to reflect losses.

Loss through surface runoff

When rainfall occurs, runoff interacts with soil and carries soluble inorganic N in the soil profile away from fields. AnnAGNPS assumes the effective depth of runoff interaction is 10 mm. This lost is different from surface inorg N loss which has been introduced in previous section.

Incorporated inorganic N from manure or other fertilizer (mnaN) is added into the inorganic fertilizer, thus fertilizer's impact on soluble N losses is reflected in elevated inorganic N level.

1). Calculate soluble inorganic N removed from soil top layer by runoff, this refers to only that which is incorporated in top soil layer

$$cell\_soil\_sol\_N = edi * \frac{inorgN * conv}{D * 1000000}$$ **Equation 9-41**

Where:

cell_soil_sol_N = mass of inorganic N removed from top soil layer through runoff (kg)

edi = effective depth of interaction factor, AnnAGNPS uses 10 mm

Denitrification Loss

surf_sol_N= mass of inorganic N in runoff from fertilizer applied on soil surface (kg)

Then, AGNPS resets mnaN and surf_inorg N values to reflect the impact of current rainfall event.

$$mnaN = mnaN + \inf\_sol\_N$$ **Equation 9-34**

$$surf\_inorgN = 0$$ **Equation 9-35**

Case 2. When rainfall is not bigger enough to generate runoff, there is no loss to surface runoff. For this situation, AnnANPS assumes that inorganic N on the soil surface either stay in place or carried into soil profile with infiltration. The amount of surface inorganic N stay on soil surface or carried into soil profile with infiltration is determined as following:

If the infiltration is greater than 1.0 mm, the surface soluble inorganic N carried into soil profile with infiltration is calculated as:

$$\inf\_sol\_N = surf\_inorgN$$ **Equation 9-36**

However, when the top soil layer is less than 200 mm, pro-rate lost to infiltration, which partition part of infiltration back to soil surface. This prevents mathematical problems later when the concentration is calculated based on the layer thickness.

$$\inf\_sol\_N = \frac{D}{200} * (\inf\_sol\_N)$$ **Equation 9-37**

Then, AGNPS resets mnaN and surf_inorg N values to reflect the impact of current rainfall event.

$$mnaN = mnaN + \inf\_sol\_N$$ **Equation 9-38**

$$surf\_inorgN = surf\_inorgN - \inf\_sol\_N$$ **Equation 9-39**

If the infiltration is less than 1.0 mm, surface inorganic N remains in place.

When rainfall occurs, it dissolves the inorganic N on the soil surface.

Case 1. When the rainfall event is bigger enough to generate runoff, runoff carries the dissolved inorganic N away from the field. In this situation, AnnANPS assumes that inorganic N on the soil surface is totally dissolved in the water and either carried away with runoff or carried into soil profile with infiltration. The amount of dissolved inorganic N carried away with runoff or carried into soil profile with infiltration is determined as following:

If the infiltration is greater than 1.0 mm, the total soluble inorganic N lost to surface runoff is calculated as:

$$surf\_sol\_N = \frac{runoff}{(runoff + \inf)} * surf\_inorgN$$ **Equation 9-28**

Inorganic N lost to infiltration is calculated as

$$\inf\_sol\_N = surf\_inorgN - surf\_sol\_N$$ **Equation 9-29**

However, when the top soil layer is less than 200 mm, pro-rate the lost to infiltration, which partition part of lost to infiltration back to lost to surface runoff. This prevents mathematical problems later when the concentration is calculated based on the layer thickness.

$$surf\_sol\_N = surf\_sol\_N + (1.0 - \frac{D}{200}) * (\inf\_sol\_N)$$ **Equation 9-30**

$$\inf\_sol\_N = \frac{D}{200} * (\inf\_sol\_N)$$ **Equation 9-31**

If the infiltration is less than 1.0 mm, the total soluble inorganic N lost to surface runoff is calculated as:

$$surf\_sol\_N = surf\_sol\_N$$ **Equation 9-32**

$$\inf\_sol\_N = 0$$ **Equation 9-33**

Where:

Inorganic N from fertilizer application is calculated using the rate of fertilizer applied for current day operation times the fertilizer inorganic N fraction (from fertilizer reference database weight/weight).

$$inorgN\_applied = (fer\_app) * (frac\_inorgN) * A_{cell} \qquad \textbf{Equation 9-23}$$

Where:

inorgN _applied = inorganic N from fertilizer application on current day (kg)
fer_app = the rate of fertilizer applied for current day operation (kg/ha)
frac_inorgN = fertilizer inorganic N fraction, from fertilizer reference database (Weight/Weight).

After a fertilizer application, the model updates the inorganic N mass balance.

a). When a soil disturbance exceeds 50 percent, for soils which the depth to imperious layer is greater or equal to 200 mm

$$mnaN = mnaN + inorgN\_applied \qquad \textbf{Equation 9-24}$$

For soils which the depth to imperious layer is less than 200 mm

$$mnaN = mnaN + \frac{D}{200} * inorgN\_applied \qquad \textbf{Equation 9-25}$$

$$surf\_inorgN = surf\_inorgN + (1 - \frac{D}{200}) * inorgN\_applied \qquad \textbf{Equation 9-26}$$

b). When a soil disturbance is less than 50 percent:

$$surf\_inorgN = surf\_inorgN + inorgN\_applied \qquad \textbf{Equation 9-27}$$

Additions added to soil profile from rainfall processes

9.2.3.1 Calculation of inorganic N additions to a cell

Added fertilizers are considered either well mixed with the top soil layer which is 200 mm or stay on soil surface based on the operation effect which is supplied by the user through operation data section. If a soil disturbance exceeds 50 percent, any fertilizer operations are considered as mixed. Otherwise, it assumes the applied fertilizer stays on soil surface. In addition, when the soil disturbance exceeds 50 percent, it not only incorporates the applied fertilizer from current operation into soil, but also incorporates any fertilizer left on the soil surface from previous fertilization.

When a soil disturbance exceeds 50 percent, fertilizers on soil surface mix with soil. The amount of fertilizer mixed with soil and the amount of fertilizer left on the soil surface after a soil disturbance is determined by the depth to the impervious layer. If the soil depth to imperious layer is greater than 200 mm (AnnAGNPS set this layer as the top soil layer, it is also called tillage layer), take all surface fertilizer and incorporate it into soil. For this case:

$$mnaN = surf\_inorgN$$ **Equation 9-19**

$$surf\_inorgN = 0$$ **Equation 9-20**

Where:

mnaN = mass of inorganic N added to a cell from incorporated inorganic additions such as fertilizers (kg). It is assumed well mixed with soil.

surf_inorgN = surface inorganic N for a cell, added through fertilization at the soil surface (kg).

Otherwise, if the soil depth to imperious layer is less than 200 mm (not many this kind of cases), to prevent the concentration of fertilizer in the top layer to skyrocket, AnnAGNPS incorporates only the pre-rated fraction of fertilizer application into the top soil layer. For this case,

$$mnaN = \frac{D}{200} * surf\_inorgN$$ **Equation 9-21**

$$surf\_inorgN = surf\_inorgN - mnaN$$ **Equation 9-22**

Fertilizer inorganic N added to a cell

$$frac\_orgN\_clay = \frac{orgN}{(frac\_clay) * 1000000} \qquad \text{Equation 9-17}$$

Where:

orgN = Concentration of organic_N in the total composite soil layer for current day(ppm).

frac_clay = fraction of clay to total composite soil.

sed_part(1,1) and sed_part(1,2) = Current day's mass of sediment (by particle size and source) at edge of cell.
Array subscript are: Particle Size (first): 1 - clay 2 - silt 3 - sand 4 - small aggregate 5 – large aggregate
Source (second): 1 - irrigation 2 - other than irrigation.

Organic nitrogen mass balance is maintained for the second soil layer which is the bottom soil layer. For second soil layer, there is not much to talk about because AnnAGNPS assumes that fertilizer application, rainfall caused runoff and sediment loss are only associated with the top soil layer. In other word, fertilizer application, rainfall does not interact with the bottom soil layer.

$$orgN_t = orgN_{t-1} - \frac{hmnN * 1000000}{conv} \qquad \text{Equation 9-18}$$

Where:

$orgN_t$ = Concentration of organic_N in the total composite soil layer for current day (ppm)

$orgN_{t-1}$ = Concentration of organic_N in the total composite soil layer for previous day (ppm)

hmnN = N mineralized from organic N in soil layer on current day (actual argument passed to inorg_N_mass_bal subroutine (kg). N mineralization is only calculated for noncrop for the second layer.

9.2.3 Inorganic Nitrogen Simulation Processes

For inorganic nitrogen, addition from fertilizer application is calculated first, followed by the losses from runoff, denitrificaiton and plant uptake. Then, mass balance was updated for inorganic nitrogen that incorporates mineralization of organic N. In other word, mineralization of organic N is not used to calculate losses from runoff, denitrificaition and plant uptake. At the end of the day, leaching loss is calculated and inorganic N is updated to reflect the leaching loss.

$$F_t = MAX(F_t, 0.1)$$ **Equation 9-13**

Water correction factor (F_w) for N mineralization is calculated as

$$F_w = \frac{SW}{f}$$ **Equation 9-14**

Where:

T_l = the average cell soil temperature (°C)

SW= the water content of soil layer on a given day (mm H_2O)

f = the water content at saturation

The correction factor (corr) is calculated as:

$$corr = sqrt(F_t * F_w)$$ **Equation 9-15**

9.2.2.4 Calculation of mass of nitrogen attached to sediment

Assumption:

a). it is the organic nitrogen makes up cell_sed_n because total nitrogen is predominantly organic nitrogen in soils.

b). the organic nitrogen is associated with clay fraction. This eliminates the need for separate nutrient enrichment ratio (Menzel; 1980 from GLEAM documentation)

$$sedN = frac\_orgN\_clay * (sed\_part(1,1) + sed\_part(1,2)) * 1000$$ **Equation 9-16**

Where:

sedN = mass of nitrogen attached to sediment (kg). Sed_part is metric tons, so multiply by 1000.

frac_ orgN_clay = decimal fraction of organic N in clay in soil layer (g/g)

$$hmnN = CMN * frac * orgN * corr * \frac{conv}{1000000}$$ **Equation 9-10**

Where:

hmnN = the mineralization rate from the humus active organic N pool (kg/d)

CMN = the humus rate constant which is approximately 0.0003 (d^{-1}), From EPIC

frac = fraction of active organic N pool

orgN = amount of organic N in the cell soil composite layers (g/Mg)

corr = corr_fact computes moisture/temperature correction factor used in N and P mineralization equations (From EPIC, Sharpley and Williams,1990) non-dimensional

conv = intensive unit to extensive unit conversion factor

The active pool fraction is calculated based on following equation:

$$frac = 0.4 * \exp(-0.0277 * YC) + 0.1$$ **Equation 9-11**

Where YC is the period of cultivation before the simulation starts (year), the concepts expressed in above equation are based on work of Hobbs and Thompson (1971). For crop land, year of cultivation is set to 50, otherwise, it is set to zero. Below the plow layer, the active pool fraction is set to 40% of plow layer value. This is based on work of Cassman and Munns (1980).

The water, temperature correction factor varies between 0 to 1.0. The calculation of correction factor is based on the temperature correction factor (F_t) and water correction factor (F_w) and is calculated the same as in EPIC. The temperature correction factor (F_t) for N mineralization is the same as in EPIC and it is calculated based on following equations:

$$F_t = \frac{T_l}{T_l + \exp(9.93 - 0.312 * T_l)} \qquad 0 < T_l < 100$$ **Equation 9-12**

$$F_t = 0 \qquad T_l <= 0$$

In order to ensure temperature correction does not fall below 0.1,

$$res\_decomp = (sub\_res) * (1 - \exp(-temp\_f * (decomp\_coeff))) * A_{cell}$$ **Equation 9-8**

Where:

sub_res = noncrop subsurface residue for a cell which is computed from RUSLE module (kg/ha),

9.2.2.2 Cell organic nitrogen from fertilizer application

Cell organic nitrogen from fertilizer application is calculated using the rate of fertilizer applied for current day operation times the fertilizer fraction which is organic nitrogen (from fertilizer reference database weight/weight).

$$fer\_orgN = (fer\_app) * (frac\_orgN) * A_{cell}$$ **Equation 9-9**

Where:

fer_orgN = organic nitrogen from fertilizer application on current day (kg)

fer_app = the rate of fertilizer applied for current day operation (kg/ha)

frac_orgN = fertilizer fraction which is organic N, from fertilizer reference database (Weight/Weight)

9.2.2.3 Mineralized nitrogen from organic nitrogen on current day

Mineralization equations are adapted from the EPIC model (Sharpley and Williams, 1990). This epic mineralization model is a modification of the PAPRAN mineralization model (Seligman and van Keulen, 1981). The model considers two sources of mineralization: the fresh organic N pool associated with crop residue and microbial biomass and the active organic N pool associated with soil humus.

Temperature, soil moisture, aeration, and PH affect N mineralization (Sharpley and Williams, 1990). Mineralization is allowed to occur only if the temperature of the soil layer is above 0°C. Mineralization is also dependent on water availability. A correction factor is used in the mineralization equations to account for the impact of temperature and water on these processes.

Mineralization from organic N pool associated with crop residue and microbial biomass is estimated for each soil layer with the equation.

$$temp\_f = \frac{3200*((T_{soil}+8)**2)-(T_{soil}+8)**4}{2560000} \qquad 0 < T_{soil} < 32 \qquad \textbf{Equation 9-5}$$

$$temp\_f = 0 \qquad T_{soil} < 0$$

$$temp\_f = 1 \qquad T_{soil} > 32$$

Where:

T_{soil} = the average cell soil temperature (°C).

Above equation is a simplification of temperature correction factor from RUSLE (Page 152, equation 5-7). The 32.0 in temp_f equation is the RUSLE (To) value (°C) which is 90 (°F), and the 8.0 is the A value, in deg. C. The equation assumes residue, irrespective of crop, is 50% organic carbon. The detail of this part is described in the cell residue calculation document.

b. Non-crop land

The cell residue nitrogen from decomposition for non-crop land is calculated for both top soil layer and bottom soil layer. It is calculated using following equations:

$$\boldsymbol{resN = (res\_decomp) * NF} \qquad \textbf{Equation 9-6}$$

Where:

resN = organic N addition from decomposition of noncrop residue (kg)

NF = nitrogen fraction of dry total biomass for non-crop field (weight of N/weight of biomass)

res_decomp = crop residue mass decomposition for current day (kg)

FN is assumed to be 1% N in dry biomass for grassland, 0.4% for forest systems, and zero for urban or mixed land.

Non-crop residue mass decomposition is calculated the same as crop residue decomposition:

c. Subsurface residue nitrogen calculation for non-crop land

$$\boldsymbol{res\_subsN = (res\_decomp) * NF} \qquad \textbf{Equation 9-7}$$

Where:

res_subsN = noncrop organic N addition from decomposed subsurface (below ground) residue

res_decomp = crop residue mass decomposition for current day (kg)

NF = nitrogen fraction of dry total biomass for non-crop field (weight of N/weight of biomass)

resN = organic N addition from decomposition of crop and noncrop residue laying on the soil surface to cell soil layer 1 on current day, (kg). Noncrop residue refers to nitrogen from litter dry biomass for noncropland surface residue that is subject to decomposition. Upon decomposition byproducts are considered mixed uniformly in soil layer 1.

fer_orgN = organic N from fertilizer application such as manure or other sources (kg)

hmnN = N mineralized from organic N in soil layer on current day (actual argument passed to inorg_N_mass_bal subroutine (kg)

sedN = current days mass of nitrogen attached to sediment (kg)

9.2.2.1 Cell Residue Nitrogen Calculations

a. Crop land

The cell residue nitrogen from decomposition is calculated only for the top soil layer for crop land. It is calculated using following equations:

$$resN = \frac{(res\_decomp)*0.5}{CNR_{harvest}}$$ **Equation 9-3**

Where:

resN = organic N addition from decomposition of crop residue (kg)

res_decomp = crop residue mass decomposition for current day (kg)

$CNR_{harvest}$ = Ratio of Carbon to Nitrogen for crop at harvest

Crop residue mass decomposition is calculated as:

$$res\_decomp = (surf\_res)*(1 - \exp(-temp\_f*(decomp\_coeff)))*A_{cell}$$ **Equation 9-4**

Where:

surf_res = surface residue for a cell which is computed from RUSLE module (kg/ha)

temp_f = RUSLE temperature correction factor (unitless)

decomp_coeff = crop surface residue decomposition coefficient (unitless)

Temperature correction factor is calculated using following equation:

9.2.1 Soil Initial Nitrogen Contents and Conversion Factor

Users can define the amount of inorganic and organic nitrogen contained in soil layers. If such information is not available, users can use default values for inorganic and organic nitrogen concentration (mg/kg or ppm). The default value for organic N is assumed as 9% of the soil organic matter; and inorganic N is assumed as 0.27% of the soil organic matter (Stevenson, 1994). Soil organic matter is usually available from national soil database such as NASIS.

The input of amount of nitrogen levels in the soil profile are as concentrations, but AnnAGNPS performs calculations on a mass basis. To convert a concentration to a mass, AnnAGNPS uses a conversion factor (conv). Conversion factor represents a weight of soil in that it is a volume of soil times bulk density. It is used to convert nutrient concentration in soil to kilograms used to do mass balances.

$$conv = D*10*1000*\rho_b*A_{cell}$$ **Equation 9-1**

Where:

conv = intensive unit to extensive unit conversion factor (kg)

D = thickness for soil layer (mm)

ρ_b = bulk density of composite soil layer (g/cc or Metric tons/ m^3)

A_{cell} = AnnAGNPS cell_area (hectares)

9.2.2 Organic Nitrogen Simulation Processes

All AnnAGNPS mass balance is based on AnnAGNPS cells and maintained for both composite soil layers.

The mass balance equation for organic nitrogen simulation processes is as followings:

$$orgN_t = orgN_{t-1} + \frac{(resN + fer \quad orgN - hmnN - sedN)*1000000}{conv}$$ **Equation 9-2**

Where:

$orgN_t$= Concentration of organic_N in the total composite soil layer for current day (ppm)

$orgN_{t-1}$ = Concentration of organic_N in the total composite soil layer for previous day (ppm)

9.1.3 Nitrogen Balance

An available nitrogen mass balance could be established through summarizing the nitrogen gains (mineralization, fixation, fertilization) and losses (plant uptake, denitrification, volatilization, and immobilization). Nitrogen could be gain or loss through exchanging with soil as absorption and desorption. However, this process usually is not simulated in nitrogen models. In addition, precipitation represents other input to the nitrogen pool. The final potential loss is nitrate leaching or through surface runoff. Factors affect nitrate leaching affect surface runoff loss too.

Because of the complex mechanisms of the nitrogen cycle in agricultural soils, long term studies of nitrogen balance in agricultural soils are very important to determine the effects of agricultural management practices on leaching of nitrate from agricultural land to groundwater and surface water. Such studies are essential for testing the long-term predictive power of models of the agricultural soil-plant nitrogen cycle, which should include calculations of mineralization, immobilization, nitrification, denitrification, crop uptake and nitrate leaching. Such models are becoming increasingly important in helping policy makers and land use managers make policy decisions. However, because of the initial condition of the soil organic matter, uncertainties in measuring mineralization and denitrification rates which cause inaccurate estimates of change in organic matter content as well as difficulties in quantifying other nitrogen processes, it is very difficult to predict nitrogen losses.

9.2 ANNAGNPS NITROGEN PROCESSES

The nitrogen cycle represented in AnnAGNPS is a simplified version of nitrogen cycle introduced in above section. AnnAGNPS tracks only major nitrogen transformations of mineralization from humified soil organic matter and plant residues, crop residue decay, fertilizer inputs, and plant uptake. Three pools of soil nitrogen are considered, stable organic N, active organic N (mineralizable N), and inorganic N. Losses (cell output pathways) include soluble inorganic N in runoff, leaching, denitrification, and sediment-bound organic N from soil erosion (Figure 9-2). The nitrogen mineralization equation is adapted from the EPIC model (Sharpley and Williams, 1990). Plant uptake of N is modeled with a simple crop growth stage index with adaptations for soil profile nutrient uptake from the TETRANS model (Corwin, 1995). Residue return and decomposition uses equations from RUSLE (Renard, et al., 1997).

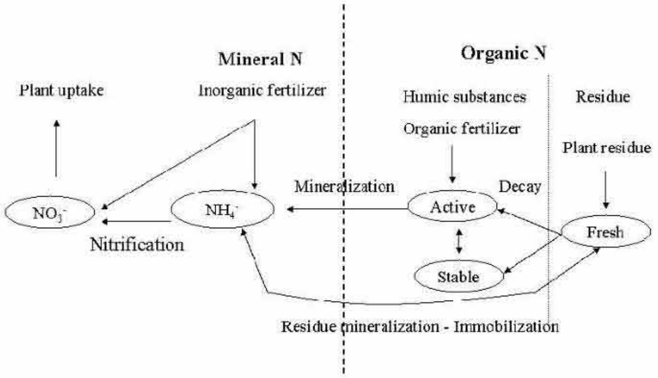

Figure 9-2. Nitrogen processes simulated in AnnAGNPS

freely drained soils depending on the drainage system. For a given site, nitrate leaching was proportional to drain flow.

Several studies showed that arable land was more prone to leaching than grass land (Kolenbrander, 1981; Barraclough et al., 1983). However, nitrate leaching losses from grazed systems is much higher than mowed grassland and arable land (Ryden, 1984).

The nature of the crop dictates the nitrogen requirement and, thus, the nitrate available for leaching. Randall et al. (1993b) investigated the effects of cropping system on nitrate leaching from tile drainage in a Minnesota clay loam soil. They concluded that the nitrogen losses from continuous corn systems were much higher than that from corn-soybean rotation systems under the fertilizer management treatment recommended to optimize yield. Kanwar and Baker (1993) conducted a similar investigation in Iowa clay soil. They also found that nitrogen losses from continuous corn systems were much higher than that from corn-soybean rotation systems. However, Melvin et al. (1993) pointed out that the corn-soybean rotation system required less fertilizer application than a continuous corn system; thus, the effects on the quality of tile drainage is from fertilizer application amount, not the crop.

Dowdell et al. (1987) compared leaching losses of nitrogen from direct drilled plots and plowed plots over four years. They found that nitrogen losses from direct drilled plots were only 48-49% of losses from plowed plots. Vinten et al. (1991) also reported greater leaching losses from plots that have been cultivated (chisel plowed and subsoiled) than from plots left stubble over the winter. The probable reason is that cultivation promotes aeration and, consequently, higher mineralization and lower denitrification losses. However, Harris et al. (1993) observed greater levels of nitrate from no-tillage plots, but they suggested that more nitrogen was lost by way of denitrification with conventional tillage.

Kanwar and Baker (1993) compared nitrate losses from tile drainage on no –tillage, chisel plow, ridge tillage and moldboard plow. They found that the greatest concentrations were measured in the drainage from moldboard plowed plots. However, the total mass of nitrate in the drainage effluent from moldboard plow was less than that from no-tillage because a larger proportion of water drains through the undisturbed soil, through fairly continuous micropores.

Naveen et al. (1996) compared the effect of no-tillage and conventional tillage on tile drain flow, nitrate concentration and loss in tile effluent in loam soil. They found that flow was significantly higher from no-tillage treatment than that from conventional tillage treatment. The flow-averaged nitrate-nitrogen concentrations in tile flow were greater from conventional tillage than that from no-tillage, but the total loss from these two treatments was not significantly different over the 40-month study period.

Mitchell et al. (1998) analyzed five years of nitrate-nitrogen data from the Little Vermilion River watershed and found that the leaching nitrate-nitrogen concentrations follow a seasonal cycle. Nitrate-nitrogen concentrations varied considerably from the tile drains between fields depending on the management system. The total loss from the grass field is 3.8kg/ha/year, 15 kg/ha/year with no-tillage corn-soybeans rotation and corn silage, and 41 kg/ha/year and 38 kg/ha/year from reduced-tillage white corn-soybeans and reduced tillage corn-soybeans respectively.

Decomposition is the breakdown of fresh organic residue into simpler organic components and adds organic nitrogen to the soil. Factors affect mineralization as talked above and the residue characteristics would affect the decomposition.

9.1.2 Nitrate Leaching and Runoff Losses

There are several combined forms of nitrogen, including fertilizer added in soils as introduced above, but only the nitrate ion is leached out of soils in appreciable amounts by water passing through the soil profile (Vinten and Smith, 1993). The movement of nitrate in the field is a complex process, and is mainly affected by the water content of the soil during leaching. Given a quantity of rainfall, the depth of water movement is different for different kinds of soils. Thus, soil structure, pore size, the spatial distribution of pores and their continuity all contribute to the irregular movement of water down the soil profile which causes the irregular movement of nitrate. The soil moisture front affects the diffusive dispersion of nitrate in the soil solution. The diffusive dispersion of nitrate in the soil solution is the nitrate movement due to the differences in nitrate concentration. Several studies have been done in modeling nitrate transport in the soil (Barraclough, 1989; Addiscott and Whitmore, 1991). The difficulties in modeling nitrate transport are in defining the highly transient nature of compounds in the nitrogen cycle. Time steps during simulation should be one hour or less; however, such data are often lacking (Vinten and Smith, 1993).

Many factors, such as fertilization, soil texture, land use, crop rotation, and cultivation can have an effect on the quantity of nitrate leached from a soil. The amount of fertilizer, the timing of fertilizer and the particular type of fertilizer used can affect the fertilizer available for crop uptake and leaching.

Bergstrom and Brink (1986) provided a general relationship between nitrogen fertilizer application and leaching losses. They conducted ten years of research on a clay soil in Sweden. They concluded that leaching of nitrate was moderate up to a rate of application of 100 kg N ha^{-1} annual^{-1}, increased rapidly thereafter, and reached a rate of 91 kg ha^{-1} for an application of 200 kg ha^{-1} in a year in which rainfall was 638 mm.

A similar study was conducted on a Minnesota silt loam soil (Randall et al., 1993a). Anhydrous ammonia was applied at rates of 0 to 252-kg ha^{-1} to different plots; they found the nitrate-nitrogen concentration in soil water increased with increasing application rates. When application rate was above 84-kg ha^{-1}, the nitrate-nitrogen concentration was above 10 mg/L. The optimum application rate for corn production was 168-kg ha^{-1}. They also concluded that fall application of fertilizer resulted in higher nitrate leaching losses than that of spring application.

Harris et al. (1984) compared the timing of fertilization on nitrogen leaching losses. They found that half of the nitrogen was lost from autumn applied nitrogen and up to 15% of nitrogen was lost from spring applied nitrogen.

Kanwar and Baker (1993) investigated the use of a single application and split applications of nitrogen fertilizer on leaching losses. The nitrate concentration in drainage water was less from split application plots.

On freely drained soils, nitrate leaching can be estimated by an estimation of water flux associated with the soil solution concentration measured. Kolenbrander (1981) found that for arable soils the leaching of nitrogen depends on soil texture, with clay soils losing about half the nitrate than from sandy soils as long as application rate did not exceed 100-200 kg/ha. Once the application rate exceeds this range, leaching losses increased rapidly and became less dependent on soil texture. The leaching of nitrogen from artificially drained soils is much larger than from

The release of nitrogen from organic matter is critical to the nitrogen cycle and to nitrate leaching in particular. A study done in England (Vinten and Smith, 1993) showed as high as 71 kg/ha/year nitrogen released from organic nitrogen in a field with no manure or N fertilizer application (Burt et al., 1993).

More than 90% of the nitrogen fertilizer used in the United States is ammonium salts (Novotny and Olem, 1994). Manure applied to the soil and septic tank sludge applied to the soil can be quickly decomposed into ammonium. Mineralization converts organic nitrogen into NH_4^+. In an aerated, microorganism-rich soil such as farmland, **nitrification** occurs which converts NH_4^+ to NO_3^- as follows:

$$\text{Organic N} \rightarrow NH_4^+ \xrightarrow{\text{Nitrosomonas}} NO_2^- \xrightarrow{\text{Nitrobacter}} NO_3^- \quad \text{(Novotny and Olem, 1994).}$$

The reaction from NO_2^- to NO_3^- is much faster than the conversion of NH_4^+ to NO_2^-. Therefore, little nitrite remains in soils. Nitrate is highly soluble and can readily move with soil water. Nitrification occurs between temperatures of 10°C to 45°C with the optimum temperature at 22°C (Stanford and Smith, 1972). Nitrification is also dependent on the soil pH value, which occurs between pH 6 to 10 with the optimum at 8.5. Additionally, nitrification depends on soil moisture content; the nitrification rate decreases with decreasing moisture content (Novotny and Olem, 1994).

However, if the soil is saturated for a long period and oxygen is absent or depleted to a point below the oxygen demand, **denitrification** occurs. In this process, NO3- is converted to NO_2, NO, N_2O and N_2 (gaseous nitrogenous forms which return to the atmosphere). This process usually occurs in subsoil with low permeability, and in soils saturated with water for a long period, such as a wetland (Carter and Allison, 1960; Firestone, 1982; Havlin et al., 1999).

The phenomenon of denitrification in soils, resulting in a loss of available nitrate has been considered a benign process in reducing the quantities of nitrate loss in surface runoff and subsurface flow such as in tile drainage or aquifers. Therefore, wetland and field ponds and control of drainage in the winter may be useful in reducing leached nitrate in tile drain systems. However, if the nitrate reduction does not go entirely to N_2 and N_2O is emitted, another environment problem is raised because N_2O is a factor in the depletion of the Earth's stratospheric ozone layer and contributes to global warming (Vinten and Smith, 1993).

Volatilization (NH_3) refers to the loss of ammonia as a gas into the atmosphere. Because NH_4^+ will more easily convert to NH_3 at high PH, the process is increased at high PH. Volatilization also increases with increase wind and temperature (Havlin et al., 1999). Since the nitrification as talked above transforms NH_4^+ to NO_3^- in hours to weeks, volatilization usually happens during a short period after ammonia-based fertilizer application. Once it becomes nitrate, it can no longer volatilize. Incorporating fertilizers, applying it right before rainstorm would push ammonia fertilizer further into soil profile where it is less available for volatilization (Reddy et al., 1979; Jones and Jacobson, 2002). In addition, applying the ammonia fertilizer in a calm day would help reduce the volatilization too.

Nitrogen fixation is the processes through which convert nitrogen gas into available forms of nitrogen. Nitrogen fixation is affected by many factors, nitrogen content, soil PH, soil moisture and plant conditions are major factors. Nitrogen fixation supplies nitrogen to microorganism and plant, increases available nitrogen level in the soil. In the United States, Nitrogen fixation produces about one third of the amount of fertilizer applied (Havlin et al., 1999).

biological and chemical processes. To understand nitrogen loss mechanisms and develop a nitrogen loading model, an understanding of nitrogen transformation in the soil and nitrogen cycle is necessary.

The general nitrogen processes in soil is illustrated in Figure 9-1. Generally, major forms of nitrogen in soils are organic N associated with humus (active and stable in organic pool), soluble forms of mineral N (mainly NO_3^- and NH_4^+, with low concentration of NO_2^-). Nitrogen cycling consists of nine major processes: plant uptake, nitrification, denitrification, volatilization, mineralization, immobilization, nitrogen fixation from the atmosphere, leaching, and decomposition of fresh residue (Figure 9-1).

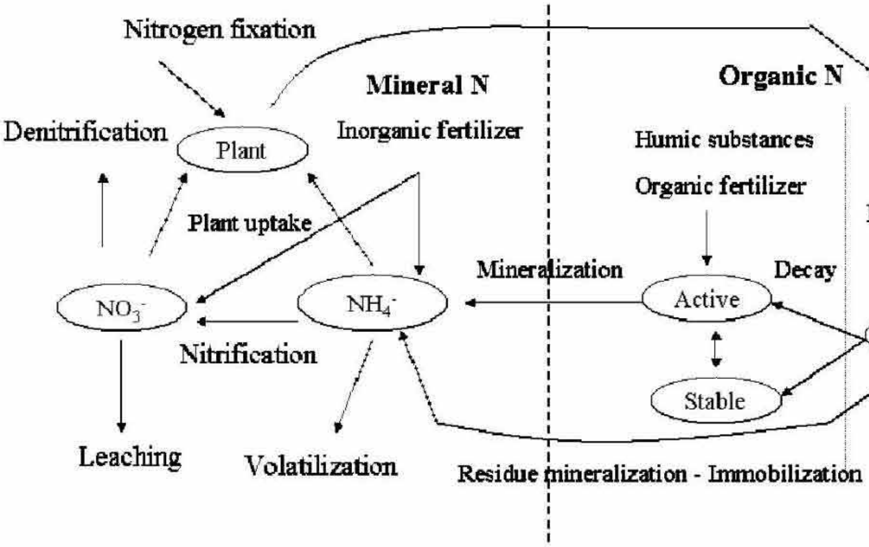

Figure 9-1. A simplification of nitrogen processes (Havlin et al., 1999)

Total nitrogen content in the natural soil top one foot ranges from 0.03% to 0.4% (Tisdale et al., 1985). The primary sources of soil nitrogen are from fertilizer application (46%), manure application (7%), N fixation from the atmosphere by symbiotic or nonsymbiotic soil bacteria (20%), plant residue (17%) and precipitation (10%) (Novotny and Olem, 1994). Most soil nitrogen is in soil organic matter which is derived from biological materials such as roots, microflora, fauna, leaf litter and humification processes (Stevenson, 1982). Organic nitrogen and ammonium nitrogen are mostly absorbed by clays. In such forms, it can be considered immobile and not available to plants. But those immobile forms can be transformed into nitrate, which is highly mobile. Mobile nitrogen can be used by plants, transported by soil water and infiltrated into ground water. Nitrogen is removed from the soil by plant uptake, surface runoff and subsurface flow (leaching), volatilization, denitrification and erosion.

Mineralization is the process that breaks down organic nitrogen compounds in the soil to release ammonium ions, NH_4^+, with the concurrent release of carbon as CO_2 in most cases (Vinten and Smith, 1993). The reverse process of mineralization is **immobilization** by which ammonium NH_4^+ is transformed into organic forms. Cropping residues, soil moisture content, soil temperature, and pH are the main factors affecting mineralization and immobilization (Stanford and Epstein, 1974; Haynes, 1986). Immobilization occurs more easily at high C:N ratios (above 30:1). In addition, nitrogen fertilizer application stimulates the mineralization process (Haynes, 1986). The promotion of mineralization of soil organic nitrogen increases the crop uptake of nitrogen (Stevenson, 1982).

8. CHEMICAL ROUTING

In general, chemicals exist in two phases: (1) dissolved (solution); and (2) attached (adsorbed) to clay-size particles.

Three nutrients are recognized by AnnAGNPS: (1) nitrogen; (2) phosphorous; & (3) organic carbon. Nitrogen & phosphorous are recognized as to be able to exist in both the soluble and adsorbed state. Organic phosphorous is assumed to be insoluble; therefore, only inorganic phosphorous is subject to equilibration. Organic carbon is assumed to be part of the clay-size particles with a known organic carbon to clay ratio.

AnnAGNPS allows any number of pesticides, each with their own independent chemical properties, but they are treated separately; i.e., there is no interaction assumed. Independent equilibration is assumed for each pesticide.

Adsorbed Chemicals: Conservation of mass calculations are made for any adsorbed chemicals if the clay-size particles are deposited within the stream reach. Re-equilibration, for the necessary chemicals, are repeated at the downstream end if clay-size particles are deposited or entrained from the bed & banks, or if there is any loss of water.

Solution Chemicals: Conservation of mass calculations are made for any chemicals in solution if there is any loss of water within the stream reach. Re-equilibration, for the necessary chemicals, are repeated at the downstream end if there is any change in the amount or source of clay-size, or if there is any loss of water.

$$M_s = M_c/(1 + K_d) \qquad \textbf{Equation 8-1}$$

Equilibration: A simple first order equilibration model for equilibration is used:

where: K_d = partition coefficient of chemical, non-dimensional;
M_c = total mass of chemical both adsorbed & in solution, Mg; and
M_s = total mass of chemical in solution, Mg.

9. NITROGEN

9.1 GENERAL INTRODUCTION

American agriculture is very important to the national economy. Sixteen percent of the gross national product of the United States is from agricultural commodities sales (Novotny and Olem, 1994). Agrichemicals such as fertilizers and pesticides have made a significant contribution in the production of agriculture. Nitrogen is one of the most important fertilizers used for agricultural production. Plants require nitrogen more than any other essential element, excluding carbon, oxygen and hydrogen.

9.1.1 Nitrogen Cycle

Nitrogen has the most complex nutrient cycle of all the mineral nutrients because nitrogen can exist as a gas in ammonia or nitrogen (Jones and Jacobson, 2002). Nitrogen dynamics in agricultural soils are very complicated

$$labP = labP - \frac{uptP * 1000000}{conv}$$ **Equation 10-73**

Where:

uptP = mass of inorganic P taken up by the plant on current day (kg)

$$mplab = \frac{labP * conv}{1000000}$$ **Equation 10-74**

Crop uptake P is calculated in a crop growth stage subroutine and passes to inorganic P balance. The crop P uptake is limited by the inorganic P available in the composite soil layer. For detail algorithms, see crop uptake section.

10.2.4 Total Inorganic P Losses to Surface Runoff

Total mass of inorganic P lost in surface runoff includes soil incorporated and surface applied P lost.

$$sol\_P = cell\_soil\_sol\_P + surf\_sol\_P$$ **Equation 10-75**

Where:

cell_soil_sol_P = nitrogen losses to runoff from composite soil layer (kg)

surf_sol_P = nitrogen losses to runoff from soil surface (kg)

sol_P = soluble P (kg).

10.2.5 Leaching

Due to the low mobility of phosphorus, AnnAGNPS does not simulate leaching of soluble P.

11. CARBON

11.1 GENERAL INTRODUCTION

$$cell\_clay\_p\_w = \frac{labP+actP+stbP}{(frac\_clay)*1000000}$$ **Equation 10-68**

Where:

cell_clay_p_w = concentration of inorganic P in clay fraction of cell soil layer (intensive units, g/g)

2). Total loss of inorganic P through soil erosion is calculated as:

$$sed\_inorgP = cell\_clay\_p\_w*(sed\_part(1,1)+sed\_part(1,2))*1000$$ **Equation 10-69**

Where:

sed_inorgP = current days mass of inorganic P attached to sediment (kg)

sed_part(1,1) and sed_part(1,2) = Current day's mass of sediment (by particle size and source) at edge of cell. Array subscript are: Particle Size (first): 1 - clay 2 - silt 3 - sand 4 - small aggregate 5 –large aggregate Source (second): 1 - irrigation 2 - other than irrigation.

sed_part is metric tons, sed_inorgP is kilograms. This is done in the same as organic P loss through soil erosion.

3). Adjust P pool values of soil layer 1 based on what was lost with sediment followed by the readjustment of fractions of each P pool.

$$labP = labP - \frac{sed\_inorgP*frac\_labP*1000000}{conv}$$ **Equation 10-70**

$$actP = actP - \frac{sed\_inorgP*frac\_actP*1000000}{conv}$$ **Equation 10-71**

$$stbP = stbP - \frac{sed\_inorgP*frac\_stbP*1000000}{conv}$$ **Equation 10-72**

Loss through plant uptake of inorganic phosphate

Amount of crop uptake P is taken off from labile P pool at the end of day.

$$soil\_sol\_P = \frac{labP}{(1. + Kd\_inorgP)}$$ **Equation 10-65**

Where:

soil_sol_P = concentration of soluble P in cell soil layer on current day, reflects inorganic P additions that are incorporated in top soil layer (intensive, units, g/Mg)

Kd_inorgP = Linear partitioning coefficient for inorganic Phosphorus. It is the ratio of the mass of absorbed P to the mass of P in solution. Kd_inorgP = 0.175 ,

labP = Amount of labile pool inorganic phosphorous in the composite cell's soil layer (g/Mg)

2). Calculate soluble inorganic P removed from soil top layer by runoff, this refers to only that which is incorporated in top soil layer

$$cell\_soil\_sol\_P = edi * \frac{soil\_sol\_P * conv}{D * 1000000}$$ **Equation 10-66**

Where:

cell_soil_sol_P = mass of inorganic P removed from top soil layer through runoff (kg)

edi = effective depth of interaction factor, AnnAGNPS uses 1 mm

3). Compute new value for labile P (in ppm) in soil top layer (reflects loss of soil soluble P)

$$labP = labP - \frac{cell\_soil\_sol\_P * 1000000}{conv}$$ **Equation 10-67**

Loss through sediment (clay-bound) inorganic P that leaves cell soil layer

When rainfall occurs, soil erosion carries inorganic P away from fields. This is calculated in the following equations. When there is no rainfall, this is not calculated.

1). Calculation of the concentration of inorganic P in clay fraction:

frac_stbP = fraction stable

. Compute mass (tons) of each pool

$$mplab = \frac{labP * conv}{1000000}$$ **Equation 10-62**

$$mpact = \frac{actP * conv}{1000000}$$ **Equation 10-63**

$$mpatb = \frac{stbP * conv}{1000000}$$ **Equation 10-64**

Where:

mplab = mass of labile P in cell soil layer (kg)
mpact = mass of active P in cell soil layer (kg)
mpstb = mass of stable P in cell soil layer (kg)
actP = active P (kg)
stbP = stable P (kg)

10.2.3.4 Calculation of inorganic P losses from a cell

This calculation will include sequential adjustments to P pool size to reflect losses.

Loss through surface runoff

When rainfall occurs, runoff interacts with soil and carries soluble inorganic P in the soil profile away from fields. AnnAGNPS assumes the effective depth of runoff interaction is 1 mm. This loss is different from surface inorg P loss which has been introduced in previous section.

Incorporated inorganic P from manure or other fertilizer (mnaP) is added into the labile and active P pools (previous section), thus fertilizer's impact on soluble P losses is reflected in elevated labile P pool levels.

1). Calculate soil soluble inorganic P, this refers to only that which is incorporated in top soil layer

$$stbP = start\_stbP + aspr$$ **Equation 10-54**

Where:

start_stbP = starting day's soil layers' stable pool of inorganic phosphorous

stbP = stable P

10.2.3.3 Calculation of additions from P mineralization

$$total\_inorgP = labP + actP + stbP$$ **Equation 10-55**

$$frac\_labP = \frac{labP}{total\_inorgP}$$ **Equation 10-56**

$$frac\_actP = \frac{actP}{total\_inorgP}$$ **Equation 10-57**

$$frac\_stbP = \frac{stbP}{total\_inorgP}$$ **Equation 10-58**

$$labP = labP + \frac{hmnP * frac\_labP * 1000000}{conv}$$ **Equation 10-59**

$$actP = actP + \frac{hmnP * frac\_actP * 1000000}{conv}$$ **Equation 10-60**

$$stbP = stbP + \frac{hmnP * frac\_stbP * 1000000}{conv}$$ **Equation 10-61**

Where:

hmnP = the mineralization rate (kg/d) from the humus active organic P pool in soil layer. It is the P mineralized from active organic P in soil layer on current day (actual argument passed to inorg_P_mass_bal subroutine (kg/d))

hmnP is from the organic P mass balance (kg)

frac_labP = fraction labile P

frac_actP = fraction active

start_ labP = comp_layer_labP

mpr = flow rate of P between labile and active P pools for soil layer j on current day (+ implies flow from labile to active pool, - in opposite direction) (g/Mg/d) (Sharpley and Williams, 1990).

Psp = soil type-dependent P sorption coefficient for soil layer j on current day, it is dimensionless (Sharpley and Williams, 1990).

mnaP = mass of inorganic (mineral) P added to a cell from incorporated inorganic additions such as fertilizers (kg). It is calculated in fertilizer section.

b). The rest of incorporated inorganic P is added into active P pool

$$actP = start\_actP + mpr + \frac{(1 - Psp) * mnaP * 1000000}{conv} - aspr$$ **Equation 10-52**

Where:

aspr = flow rate of P between active and stable P pools for soil layer j on current day (+ implies flow from active to stable pool, - implies flow in opposite direction (g/Mg/d), following section introduces the calculation of aspr

if the actP is less than zero, then readjust the aspr value as follow:

$$aspr = start\_actP + mpr + \frac{(1 - Psp) * mnaP * 1000000}{conv}$$ **Equation 10-53**

And set the actP as zero

c). Compute stable P pool size