COUPLED SIMULATION MODELING OF FLATWOODS HYDROLOGY, NUTRIENT AND VEGETATION DYNAMICS

By

LEI YANG

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2006
Copyright 2006

by

Lei Yang
This dissertation is dedicated to

my parents,
my high school teacher Zhiting Wang,
and my friend Joseph S. Smith.

I recognize and appreciate the life-long influence they brought to me at different stages of my life.
ACKNOWLEDGMENTS

I am greatly indebted to my supervisor, Dr. Wendy D. Graham, for her constant guidance, insight, encouragement, and continuous support as well as confidence in my research over the past five years. Her thorough and thoughtful coaching with all aspects of my research was unselfishly tireless, and her enthusiasm for research and quest for excellence have left me an everlasting impression. I would like to express sincere appreciation to Dr. Kenneth L. Campbell for his invaluable advice on addressing each of my technical problems and concerns. Without his constant supervision and guidance throughout the model development, the completion of this model would have been impossible. I am grateful to Dr. James W. Jones for his insight and invaluable advice on the methodology of the vegetation dynamic model and support in offering important crop growth model related literature; to Dr. Mark W. Clark for introducing me to the niche theory and the interactive relationship between wetland hydrology and vegetation dynamics and his help in identifying pasture vegetation species for simulation; to Dr. Gregory A. Kiker for introducing me to the Java programming language with his great enthusiasm and his technical support regarding the ACRU2000 modeling system during the model development. I deeply benefited from many hours of precious discussions with each of these committee members on a multitude of perspectives regarding my research. Without their combined supervision of each step throughout my research, this study would not have been possible.
I would like to acknowledge my debt to Chris Martinez for his great cooperation as a teammate throughout the development of hydrologic and nutrient models. I wish also to thank Dr. Michael D. Annable for his generous comments on specific technical problems during many brown-bag group meetings; Dr. Patrick Bohlen in MacArthur Agro-ecology Research Center, Florida, for introducing me to the pasture sites at Buck Island Ranch and offering useful documents; Mr. Gregory S. Hendricks for offerings of data for Buck Island Ranch and nutrient related documents; Dr. Stuart J. Rymph from the University of Wisconsin for providing important bahiagrass related documents; Ms. Cheryl H. Porter for offering crop modeling documents; and Dr. William Wise and his graduate student Min Joong Hyuk for helping with DHI software.

Also, special thanks go to a few friends including Joseph S. Smith, Tricia G. Smith, Donna L. Miller, Paul Miller, and David R. Murphy for their friendship and support throughout the past few years, especially during some tough times. I would like to acknowledge all the good friends for their friendship. I am also grateful to several labmates for their friendship and encouragement, and faculty, staff and students in the Agricultural and Biological Engineering Department for the quality academic environment.

Finally I particularly appreciate my parents and siblings for their unconditional love, understanding, patience and encouragement. Without their affection, it would have been even more difficult to complete this research.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ACKNOWLEDGMENTS</th>
<th>iv</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xiii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>xx</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Study Background</td>
<td>1</td>
</tr>
<tr>
<td>Overview of the Coupled Modeling System</td>
<td>8</td>
</tr>
<tr>
<td>Study Objectives</td>
<td>9</td>
</tr>
<tr>
<td>2 LITERATURE REVIEW</td>
<td>12</td>
</tr>
<tr>
<td>Overview of Previous Modeling Efforts</td>
<td>12</td>
</tr>
<tr>
<td>ACRU2000 Modeling System</td>
<td>20</td>
</tr>
<tr>
<td>Model Testing Procedures</td>
<td>24</td>
</tr>
<tr>
<td>Model Calibration</td>
<td>25</td>
</tr>
<tr>
<td>Model Validation</td>
<td>25</td>
</tr>
<tr>
<td>Sensitivity Analysis</td>
<td>26</td>
</tr>
<tr>
<td>Model Evaluation</td>
<td>28</td>
</tr>
<tr>
<td>Statistics</td>
<td>28</td>
</tr>
<tr>
<td>Graphic representation</td>
<td>31</td>
</tr>
<tr>
<td>3 HYDROLOGIC SIMULATION MODEL</td>
<td>34</td>
</tr>
<tr>
<td>Introduction</td>
<td>34</td>
</tr>
<tr>
<td>Vertical Hydrologic Components</td>
<td>38</td>
</tr>
<tr>
<td>Rainfall</td>
<td>38</td>
</tr>
<tr>
<td>Canopy Interception</td>
<td>38</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>39</td>
</tr>
<tr>
<td>Infiltration</td>
<td>42</td>
</tr>
<tr>
<td>Soil Water Redistribution</td>
<td>42</td>
</tr>
<tr>
<td>Upward Flux</td>
<td>43</td>
</tr>
<tr>
<td>Deep Seepage</td>
<td>44</td>
</tr>
</tbody>
</table>
# Horizontal Hydrologic Components

- **Overland Flow** ................................................................. 45
  - Overland flow calculation ................................................ 46
  - Surface water storage apportionment .............................. 49
- **Groundwater Flow** .......................................................... 51
  - Lateral groundwater flow calculation ......................... 54
  - Groundwater storage apportionment ............................ 56
- **Canal Flow** ................................................................................ 56

## Initial and Boundary Conditions

- **Model Testing and Validation** ........................................ 58
  - Simulation Sequence and Model Performance Accuracy Analysis ................ 58
    - Case 1: Overland flow along a flat rectangular plane ............... 60
    - Case 2: Overland and groundwater flow over an axisymmetric domain .... 65
  - Application at Dry Lake Dairy #1, Kissimmee River Basin, Florida ......... 76
    - Site description ................................................................. 76
    - Results and discussion .................................................... 79

## Concluding Remarks

---

# 4 NUTRIENT SIMULATION MODEL

## Introduction

- **Nutrient Components** ...................................................... 89
  - Nitrogen Cycle Components ........................................ 89
    - Mineralization ......................................................... 91
    - Immobilization ....................................................... 92
    - Denitrification ....................................................... 92
    - Runoff, sediment transport and percolation .................. 93
    - Uptake, evaporation, and fixation .............................. 94
    - Rainfall and fertilizer ............................................. 95
    - Ammonia volatilization .......................................... 95
    - Surface and subsurface lateral nitrate nitrogen transport ....... 95
    - Surface and subsurface lateral ammonium nitrogen transport .......... 97
  - Phosphorus Cycle Components .................................. 98
    - Mineralization ....................................................... 99
    - Immobilization ....................................................... 100
    - Runoff, sediment, percolation ................................ 100
    - Uptake and evaporation ......................................... 101
    - Rainfall and fertilizer ........................................... 101
    - Surface and subsurface lateral labile phosphorus transport .......... 102
  - Conservative Solute Transport Components .................. 104
    - Initial and Boundary Conditions ............................. 105
    - Model Testing and Validation ................................ 106
      - Conservative Solute Test .................................... 106
        - Scenario description ...................................... 107
        - Results and discussion .................................. 107
      - Application at Buck Island Ranch, Lake Okeechobee Basin, Florida ... 111
        - Project description ........................................ 111
Sensitivity analysis........................................................................................117
Results and discussion..................................................................................122
Concluding Remarks ........................................................................................133

5 VEGETATION DYNAMICS SIMULATION MODEL .........................................189

Introduction...............................................................................................................189
Methodology.............................................................................................................192
    Model Structure.................................................................................................192
    Plant Growth......................................................................................................193
        Potential growth..........................................................................................193
        Reduced growth.........................................................................................196
        Dry matter partitioning..............................................................................197
    Leaf Area Index .................................................................................................197
    Plant Senescence ...............................................................................................198
    Evapotranspiration............................................................................................200
    Nitrogen Uptake ................................................................................................201
    Phosphorus Uptake............................................................................................204
    Growth Reduction Factor ..................................................................................205
        Water stress and logging factors ...............................................................206
        Nitrogen stress factor .................................................................................208
        Phosphorus stress factor ............................................................................209
Hypothetical Scenario Model Testing .................................................................209
    Scenario Description .........................................................................................209
Results and Discussion......................................................................................213
    Water and nutrient responses to water retention BMP.....................................213
    Influence of differences in temperature sensitivities among species ..........214
    Species composition dynamics due to water retention BMP .........................216
Concluding Remarks ..........................................................................................219

6 SUMMARY AND CONCLUSIONS .......................................................................234

Hydrologic Simulation Model ..................................................................................235
Nutrient Simulation Model.......................................................................................236
Vegetation Dynamics Simulation Model..................................................................237
Implications of the Research ................................................................................238
Future Research Recommendations .......................................................................238
    Model Pre- and Post-processing Capacity.......................................................238
    Use Consistent Units for Parameters and Variables........................................239
    Documentation ................................................................................................239
    Potential Changes to Existing Objects ............................................................239
    Sub-Daily Time Step .......................................................................................240
    Herbivore Movement Module ........................................................................240
    Hydrologic Model ............................................................................................240
    Nutrient Model ................................................................................................241
    Vegetation Model .............................................................................................241
APPENDIX

A  FLOW CHART FOR THE COUPLED MODELING SYSTEM AND MODEL PROCESSES ..................................................................................................................242

B  FLOW CHART OF LATERAL GROUNDWATER FLOW SIMULATION........247

C  LISTS OF NEW AND MODIFIED OBJECTS .......................................................248

D  LISTS OF NEW INPUT AND OUTPUT VARIABLES ........................................262

E  LISTS OF MODEL INPUT FILES ......................................................................265

F  ALGORITHMS OF WATER STORAGE APPORTIONMENT ..............................266

LIST OF REFERENCES ..........................................................................................282

BIOGRAPHICAL SKETCH ....................................................................................293
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>List of strategies for water transmission and water storage updating for simulation sequence experiments.</td>
<td>59</td>
</tr>
<tr>
<td>3-2</td>
<td>Statistics for the surface water depths predicted by the modified ACRU2000 model and MIKE SHE for the three experiments with the same simulation sequence.</td>
<td>62</td>
</tr>
<tr>
<td>3-3</td>
<td>Statistics for the surface water depths predicted by the modified ACRU2000 model and MIKE SHE for the three experiments.</td>
<td>69</td>
</tr>
<tr>
<td>3-4</td>
<td>Statistics for the simulated groundwater table depths by the modified ACRU2000 model, MIKE SHE, and MODFLOW for the three experiments with the same simulation sequence.</td>
<td>75</td>
</tr>
<tr>
<td>3-5</td>
<td>Summary of annual water budget on Dry Lake Dairy #1 site.</td>
<td>78</td>
</tr>
<tr>
<td>3-6</td>
<td>Model input parameters for the Dry Lake Dairy #1 site.</td>
<td>85</td>
</tr>
<tr>
<td>3-7</td>
<td>Statistics for the simulated surface runoff and groundwater table depths by the modified ACRU2000 and FHANTM.</td>
<td>85</td>
</tr>
<tr>
<td>4-1</td>
<td>Statistics for the solute mass predicted by the modified ACRU2000.</td>
<td>108</td>
</tr>
<tr>
<td>4-2</td>
<td>List of stocking activities for pastures S1, S4, W6 and W7.</td>
<td>137</td>
</tr>
<tr>
<td>4-3</td>
<td>List of fertilization activities for pastures S1 and S4.</td>
<td>137</td>
</tr>
<tr>
<td>4-4</td>
<td>List of burn activities for pastures S1, S4, W6 and W7.</td>
<td>137</td>
</tr>
<tr>
<td>4-5</td>
<td>Percent of area occupied by different soil series and wetlands in selected summer and winter pastures.</td>
<td>137</td>
</tr>
<tr>
<td>4-6</td>
<td>Model input parameters for the winter pastures W6 and W7.</td>
<td>138</td>
</tr>
<tr>
<td>4-7</td>
<td>Model input parameters for the summer pastures S4 and S1.</td>
<td>139</td>
</tr>
<tr>
<td>4-8</td>
<td>Selected hydrologic parameters for sensitivity analysis for W6.</td>
<td>140</td>
</tr>
<tr>
<td>4-9</td>
<td>Selected nutrient parameters for sensitivity analysis for W6.</td>
<td>141</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4-31</td>
<td>Annual statistics for the verification site S1</td>
<td>148</td>
</tr>
<tr>
<td>5-1</td>
<td>Percent cover of vegetation on summer pastures S4</td>
<td>222</td>
</tr>
<tr>
<td>5-2</td>
<td>Parameter values for the different plant species for the vegetation model</td>
<td>222</td>
</tr>
<tr>
<td>5-3</td>
<td>Initial composition percentage and amount for species in each land segment</td>
<td>223</td>
</tr>
<tr>
<td>5-4</td>
<td>Variables calculated from other models</td>
<td>223</td>
</tr>
<tr>
<td>5-5</td>
<td>Output variables from the vegetation model</td>
<td>223</td>
</tr>
<tr>
<td>5-6</td>
<td>Testing scenarios for temperature functions</td>
<td>223</td>
</tr>
<tr>
<td>E-1</td>
<td>New input and output variables required towards the multi-directional spatial simulation beyond the existing variables in ACRU2000</td>
<td>262</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Schematic of the feedback relationships among hydrology, nutrient, and vegetation dynamics in the coupled model system</td>
<td>8</td>
</tr>
<tr>
<td>2-1</td>
<td>General structure of the lumped ACRU (v3.00) model</td>
<td>21</td>
</tr>
<tr>
<td>2-2</td>
<td>Land segment configuration of the ACRU2000 model</td>
<td>23</td>
</tr>
<tr>
<td>3-1</td>
<td>Schematic of an example catchment and its spatial discretization.</td>
<td>35</td>
</tr>
<tr>
<td>3-2</td>
<td>Hydrological processes in the modified ACRU2000 hydrologic model</td>
<td>36</td>
</tr>
<tr>
<td>3-3</td>
<td>Configuration of overland flows between source land segment and adjacent land segments</td>
<td>46</td>
</tr>
<tr>
<td>3-4</td>
<td>The relationship between Manning's roughness-coefficient (n) to water depth and to plant height, both of which change dynamically in the model</td>
<td>48</td>
</tr>
<tr>
<td>3-5</td>
<td>Structured boundary</td>
<td>49</td>
</tr>
<tr>
<td>3-6</td>
<td>Schematic representation of the lateral groundwater flow from the higher head $h_s$ to the lower head $h_d$. (A) and (B) represent the situations without and with overland flow, respectively</td>
<td>52</td>
</tr>
<tr>
<td>3-7</td>
<td>Diagram of lateral groundwater flow between two land segments. (A) and (B) represent the generalized situations without and with overland flow, respectively.</td>
<td>53</td>
</tr>
<tr>
<td>3-8</td>
<td>A rectangular plane with 20 land segments (arrow indicates water movement direction and digits assigned in each grid cell indicate the number for each land segment)</td>
<td>60</td>
</tr>
<tr>
<td>3-9</td>
<td>Comparisons of the simulated surface water depth from the modified ACRU2000 model on the three experiments between two opposite simulation sequences</td>
<td>63</td>
</tr>
<tr>
<td>3-10</td>
<td>Comparisons of the simulated surface water depths between the MIKE SHE’s overland flow model and the modified ACRU2000 hydrologic model on the three experiments with the simulation sequence from LS1 to LS20.</td>
<td>64</td>
</tr>
</tbody>
</table>
3-11 Schematics of two-dimensional axisymmetric domain (left) and its three-dimensional discretization (right). The digits assigned in the left diagram indicate the number for each land segment............................................................66

3-12 Comparisons of simulated water depths of the selected land segments between the modified ACRU2000 model and the MIKE SHE’s overland flow model for the three experiments............................................................................................68

3-13 Comparisons of the simulated water depths of the selected land segments between the modified ACRU2000 and MIKE SHE’s overland flow model for Experiment 3............................................................70

3-14 Comparisons of the groundwater table depths at the selected land segments between and the modified ACRU2000 hydrologic model and MIKE SHE’s groundwater flow model for the three experiments............................................................74

3-15 Location of Dry Lake Dairy #1 site.................................................................76

3-16 Dry Lake Dairy # 1 site map, topographic survey and location of well stations and tracer application compound. Distance scales are in feet and elevation contours are in feet above mean sea level..............................................................77

3-17 Comparisons of the continuous simulations of runoff from the modified ACRU2000 and FHANTM against the observed data. .........................................................84

3-18 Comparisons of the cumulative simulated runoff from the modified ACRU2000 and FHANTM with the cumulative observed data.........................................................84

3-19 Comparisons of the continuous simulation of groundwater table depths from the modified ACRU2000 and FHANTM against the observed data.....................................85

3-20 Scatterplots of observed vs. simulated surface runoff depths predicted by the modified ACRU2000 and FHANTM..............................................................86

3-21 Scatterplots of observed vs. simulated groundwater table depths predicted by the modified ACRU2000 and FHANTM..............................................................86

4-1 Schematic representation of the GLEAMS nitrogen cycle......................................90

4-2 Schematic representation of the GLEAMS phosphorus cycle................................98

4-3 Comparisons of the solute mass in the 3rd and 4th soil layers of selected land segments between the modified ACRU2000 and PMPATH..........................................110

4-4 Location of MacArthur Agro-ecology Research Center....................................111

4-5 General layout of the project field . ..................................................................113
4-6 Relative sensitivities of the total surface runoff of 6-year simulation period over the selected input parameters for the pasture sites W6 and S4.........................149

4-7 Relative sensitivities of the maximum water table depth of 6-year simulation period over the selected input parameters for the pasture sites W6 and S4.........150

4-8 Relative sensitivities of the total P load of 6-year simulation period over the selected input parameters and variables for the pasture sites W6 and S4............151

4-9 Relative sensitivities of the total N load of 6-year simulation period over the selected input parameters for the pasture sites W6 and S4..................................152

4-10 Continuous simulation of groundwater table depth from September 2000 through December 2003 for the calibration site W6............................................153

4-11 Continuous simulation of groundwater table depth from September 2000 through December 2003 for the verification site W7. ...........................................153

4-12 Continuous simulation of groundwater table depth from September 2000 through December 2003 for the calibration site S4. ............................................154

4-13 Continuous simulation of groundwater table depth from September 2000 through December 2003 for the verification site S1............................................154

4-14 Continuous simulation of surface runoff from July 1998 through December 2003 for the calibration site W6..........................................................155

4-15 Continuous simulation of surface runoff from July 1998 through December 2003 for the verification site W7..........................................................155

4-16 Continuous simulation of surface runoff from July 1998 through December 2003 for the calibration site S4. ..........................................................156

4-17 Continuous simulation of surface runoff from July 1998 through December 2003 for the verification site S1..........................................................156

4-18 Continuous simulation of P loads from July 1998 through December 2003 for the calibration site W6. ..........................................................157

4-19 Continuous simulation of P loads from July 1998 through December 2003 for the verification site W7..........................................................157

4-20 Continuous simulation of P loads from July 1998 through December 2003 for the calibration site S4. ..........................................................158

4-21 Continuous simulation of P loads from July 1998 through December 2003 for the verification site S1. ..........................................................158
4-22 Continuous simulation of N loads from July 1998 through December 2003 for the calibration site W6. ........................................................................................159

4-23 Continuous simulation of N loads from July 1998 through December 2003 for the verification site W7. ........................................................................................159

4-24 Continuous simulation of N loads from July 1998 through December 2003 for the calibration site S4. ........................................................................................160

4-25 Continuous simulation of N loads from July 1998 through December 2003 for the verification site S1. ........................................................................................160

4-26 Continuous simulation of surface runoff P concentrations from July 1998 through December 2003 for the calibration site W6. ............................................161

4-27 Continuous simulation of surface runoff P concentrations from July 1998 through December 2003 for the verification site W7. ............................................161

4-28 Continuous simulation of surface runoff N concentrations from July 1998 through December 2003 for the calibration site W6. ............................................162

4-29 Continuous simulation of surface runoff N concentrations from July 1998 through December 2003 for the verification site W7. ............................................162

4-30 Continuous simulation of surface runoff P concentrations from July 1998 through December 2003 for the calibration site S4. ............................................163

4-31 Continuous simulation of surface runoff P concentrations from July 1998 through December 2003 for the verification site S1. ............................................163

4-32 Continuous simulation of surface runoff N concentrations from July 1998 through December 2003 for the calibration site S4. ............................................164

4-33 Continuous simulation of surface runoff N concentrations from July 1998 through December 2003 for the verification site S1. ............................................164

4-34 Linear plots of monthly and annual surface runoff from 1998 to 2003 for the calibration site W6. ........................................................................................165

4-35 Linear plots of monthly and annual surface runoff from 1998 to 2003 for the verification site W7. ........................................................................................166

4-36 Linear plots of monthly and annual water table depth from 1998 to 2003 for the calibration site W6. ........................................................................................167

4-37 Linear plots of monthly and annual water table depth from 1998 to 2003 for the verification site W7. ........................................................................................168
4-38 Linear plots of monthly and annual P load from 1998 to 2003 for the calibration site W6. ................................................................................................................169

4-39 Linear plots of monthly and annual P load from 1998 to 2003 for the verification site W7..............................................................................................170

4-40 Linear plots of monthly and annual N load from 1998 to 2003 for the calibration site W6. ................................................................................................................171

4-41 Linear plots of monthly and annual N load from 1998 to 2003 for the verification site W7..............................................................................................172

4-42 Linear plots of monthly and annual surface runoff from 1998 to 2003 for the calibration site S4.................................................................................................173

4-43 Linear plots of monthly and annual surface runoff from 1998 to 2003 for the verification site S1. ..............................................................................................174

4-44 Linear plots of monthly and annual water table depth from 1998 to 2003 for the calibration site S4.................................................................................................175

4-45 Linear plots of monthly and annual water table depth from 1998 to 2003 for the verification site S1. ..............................................................................................176

4-46 Linear plots of monthly and annual P load from 1998 to 2003 for the calibration site S4...................................................................................................................177

4-47 Linear plots of monthly and annual P load from 1998 to 2003 for the verification site S1. ..............................................................................................178

4-48 Linear plots of monthly and annual N load from 1998 to 2003 for the calibration site S4...................................................................................................................179

4-49 Linear plots of monthly and annual N load from 1998 to 2003 for the verification site S1. ..............................................................................................180

4-50 Duration curves of daily surface runoff and water table depth for the calibration site W6. ................................................................................................................181

4-51 Duration curves of daily P and N loads for the calibration site W6. ................182

4-52 Duration curves of daily surface runoff and water table depth for the verification site W7. ................................................................................................................183

4-53 Duration curves of daily P and N loads for the verification site W7..............184

4-54 Duration curves of daily surface runoff and water table depth from 1998 to 2003 for the calibration site S4. ................................................................................................................185
4-55 Duration curves of daily N and P loads from 1998 to 2003 for the calibration site S4..........................................................186

4-56 Duration curves of daily surface runoff and water table depth from 1998 to 2003 for the verification site S1.................................187

4-57 Duration curves of daily N and P loads from 1998 to 2003 for the verification site S1..........................................................188

5-1 Diagram for daily plant growth in relation to weather and water and nutrient availabilities (DM = dry matter; N = nitrogen; P = phosphorus; and SLA = specific leaf area) .................................................................193

5-2 Diagram of temperature function for species i. ........................................195

5-3 An example relationship between plant biomass nitrogen concentration and growth ratio........................................................202

5-4 An example relationship between plant biomass phosphorus concentration and growth ratio..................................................204

5-5 Aerial photo showing the layout of the improved summer pasture site S4 and location of associated instrumentation. S1 to S6 indicate the individual summer pasture sites and LS1 to LS12 indicate the land segments divided for the site S4. The dotted lines were made to show the boundary between land segments........210

5-6 Continuous simulation of surface runoff throughout the simulation period from 1998 to 2003..................................................224

5-7 Continuous simulation of water table depths at land segment 9 throughout the simulation period from 1998 to 2003..........................224

5-8 Continuous simulation of P loads throughout the simulation period from 1998 to 2003.............................................................225

5-9 Continuous simulation of N loads throughout the simulation period from 1998 to 2003.............................................................225

5-10 Continuous simulation of P concentrations throughout the simulation period from 1998 to 2003.............................................226

5-11 Continuous simulation of N concentrations throughout the simulation period from 1998 to 2003.............................................226

5-12 Comparison of predicted potential aboveground biomass for species in land segment 11 with different temperature functions........227
5-13 Comparison of temperature factors among the three selected species in land segment 11. ..................................................................................................................228

5-14 Species distribution (percent of total aboveground biomass at the end of each year) over land segments for bahia, floralta and panicum throughout the simulation period from 1998 to 2003.................................................................230

5-15 Comparisons of continuous simulation of aboveground biomass for all species in the selected land segments 8, 11, and 12 before water retention BMP. ........231

5-16 Comparisons of continuous simulation of aboveground biomass for all species in the selected land segments 8, 11, and 12 after water retention BMP. ..........232

5-17 Growth limiting factors for bahiagrass in land segment 8 before water retention BMP was applied. ...........................................................................................................233

G-1 Single land segment type neighbor receiving overland flow.....................266

G-2 Single river type neighbor receiving overland flow ....................................267

G-3 Configuration of multiple directional overland flows from source land segment to adjacent land segments. .....................................................................................269
Lake Okeechobee, located at the center of the Kissimmee-Okeechobee-Everglades aquatic ecosystem in south Florida, is experiencing water quality degradation. Non-point agricultural runoff from dairies and cow-calf operations in the northern watershed of the lake is considered to be the primary source of excess phosphorus (P) loading discharged into the lake. In order to evaluate alternative land management practices that result in reduced P loading from the watershed to the lake, a coupled modeling system integrating hydrology, nutrient and vegetation dynamics simulation was developed.

The coupled modeling system was developed within the Java-based, object-oriented framework of the ACRU2000 modeling system by adding new hydrologic and nutrient components and a vegetation model to enable multi-directional spatial simulation of hydrological, chemical, and biological processes simultaneously in a daily time step. The coupled model was tested for accuracy by comparing performance with well-accepted models including MIKE SHE and MODFLOW. Results indicate that the
coupled model is capable of simulating, with reasonable accuracy, hydrological and solute transport processes for the hypothetical scenarios. Additionally, the model was tested in the Kissimmee River Basin and Lake Okeechobee Basin by comparing with the FHANTM model and against measured data. These applications demonstrated that the coupled model is statistically close to the performance of FHANTM with respect to hydrologic response in the Kissimmee River Basin, but much better than FHANTM with regard to hydrologic and nutrient responses in the Lake Okeechobee Basin. From the testing, it was concluded that the model is able to continuously simulate the surface runoff and groundwater tables with adequate accuracy. However the model’s capacity to simulate nutrient loading needs further testing after sufficient reliable nutrient data becomes available. The vegetation model, coupled with the hydrologic and nutrient models, was tested for a hypothetical scenario based on the conditions in the Lake Okeechobee Basin. The test results show that the temporal and spatial vegetation composition pattern can be an indicator of the ecohydrological impacts of alternative land management practices. However, for actual application of this model, further testing is required when more vegetation data are available.

Recommended future research includes further development of the coupled model to enable a user-friendly pre- and post-processing graphical interface, an option for sub-daily time steps, beef-cattle roaming simulation, and plant competition. Further testing of the coupled model should be conducted at larger watershed scales and for the nutrient and vegetation simulations when additional data are available.
CHAPTER 1
INTRODUCTION

Study Background

Lake Okeechobee is a large, multi-functional lake located at the center of the
Kissimmee-Okeechobee-Everglades aquatic ecosystem in south Florida. The lake
provides regional flood protection, water supply for agricultural, urban and natural areas,
and is a critical habitat for fish, birds and other wildlife. Water quality in the lake has
declined over recent decades due to urban development, channelization of the Kissimmee
River and agricultural operations. The 1997 Lake Okeechobee Surface Water
Improvement and Management Plan (South Florida Water Management District
[SFWMD], 1997a) found that excess phosphorus (P) loading is one of the most serious
problems the lake is facing.

The Lake Okeechobee watershed, with an area of 12,000 km² extending from
Orlando to the Everglades, lies predominately in the southern Florida flatwoods
physiographic region characterized by flat, poorly drained, high-water table, and fine
sandy soils, which consist of Spodosols, Entisols, and Histosols (United States
Department of Agriculture [USDA], 1990). The majority of the soils in the northern
watersheds of the lake are Sposodols, with 8-20 cm thick surface horizons underlain by
spodic horizons at depth of 0.5 m to greater than 2 m (USDA, 1990). These soils, with
greater than 90% sand, are characterized by high infiltration rates and poor internal
drainage due to low permeability of the spodic horizon. When rainfall occurs, the soils
often become saturated in a short time. The water table is commonly within 1 m of the
ground surface during the wet season and may recede to 2 m depth during the dry season (Knisel et al., 1985). With highly permeable surface soils there is little surface runoff until the soil pore space is filled with water and the water table reaches the surface (Heatwole et al., 1987); slow downward or lateral movement of water and solutes occurs with water table recession.

The land use in the Okeechobee watershed is primarily beef cattle, dairy, and citrus. Since 1930, ranching has intensified from native pastures to improved pastures with high quality grasses and legumes, drainage and fertilization. During the 1950s, the dairy industry first moved to Okeechobee County, and by the mid-1980s, there were 49 milking barns and 50,000 milk cows in the lower Kissimmee River (LKR) and Taylor Creek/Nubbin Slough (TCNS) regions (Flaig and Reddy, 1995). The primary feed for dairy cows, including high P containing materials, was imported into the watershed. Animal waste management was almost non-existent until the 1970s (Flaig and Reddy, 1995). Historically, the majority of P load to the lake was derived from the LKR and the TCNS basins with 13% contributed by the LKR basin and 22% by the TCNS basin. With the implementation of improved management practices during recent decades, the P load from the TCNS basin has decreased by 17% (Gunsalus et al., 1992), and the LKR basin now provides the greatest P load to the lake. Previous studies have indicated that non-point agricultural runoff in the northern watershed of the lake is considered to be the primary source of excess P being discharged into Lake Okeechobee, which typically exceeds the recommended total maximum daily loading (TMDL = 140 metric ton/year). P in agricultural runoff mainly originates from one or more of four sources: fertilizers,
animal manures, mineralization of organic materials, and/or atmospheric deposition. The first three sources can be controlled by agricultural best management practices.

In order to protect the water quality of Lake Okeechobee and reach environmental restoration goals, a variety of best management practices (BMPs) have been implemented in the Lake Okeechobee watershed. BMPs are on-farm activities designed to reduce nutrient losses in drainage waters to an environmentally acceptable level, while simultaneously maintaining an economically viable farming operation (Bottcher et al., 1995). To reduce P loading one must either reduce P concentration or water volume. According to Bottcher et al. (1995), there are three ways to reduce P concentrations in the runoff water from agriculture: 1) reduce the amount of P on the farm by minimizing P inputs to the farm and maximizing non-runoff P output from the farm; 2) reduce the hydrologic mobility of the P that is on the farm by limiting water contact and/or reducing the solubility or erodibility of phosphatic materials; 3) edge of field/farm pre-discharge treatment using uptake, adsorption, deposition, or precipitation technologies, such as wetland and/or chemical additives. There are two methods used to reduce water runoff volume: 1) increase the evapotranspiration from the farm; 2) decrease off-farm or groundwater irrigation water inputs to the farm by improved irrigation efficiency or by using storage runoff as a substitute irrigation supply. From numerous studies in the Okeechobee basin as well as generally accepted practices from other parts of the country, Bottcher et al. (1995) summarized the BMPs appropriate for the Lake Okeechobee basin as follows: 1) fertility BMPs including calibrated soil testing (CST), banding of fertilizer, prevention of misplaced fertilizer, and split application; 2) animal manure BMPs including dairy high intensity area (HIA) drainage control, collection and distribution of
barn manure, watering, feed and shade facilities placement, fencing animals from ditches and streams, grazing management, selecting high P uptake crops from manure application areas, and composting; 3) general BMPs including crop management, irrigation and drainage management, maximum flow distance for P control, flow-way buffer strips, limit drainage of organic and/or wetland soils, and alternative land use; 4) edge-of-field/farm treatment including runoff retention/detention system, use of wetlands, and chemical treatment.

Only a few of the above listed BMPs have been field tested, and even those were tested for only a limited set of conditions (Bottcher et al., 1995). Flaig and Reddy (1995) indicated that implementation of BMPs has not been sufficient to meet P load reduction goals, and additional P control practices to further reduce P are needed. Recent BMPs efforts to reduce nutrient loading from the Lake Okeechobee watershed have focused on restoration of wetlands for their particular capacities to reduce nutrient loadings, thereby reducing eutrophication in adjacent water bodies.

Wetlands are an important component of the Lake Okeechobee watershed. However, many of these wetlands have disappeared or have been degraded due to hydrologic alteration, urbanization and agricultural practices. Seasonal and year-round isolated and connected wetlands used to occupy 25% of the watershed area (McCaffery et al., 1976). Now many isolated wetlands are connected by shallow drainage ditches and have been converted into pastures. Currently, wetlands represent about 15% of the land area in the Lake Okeechobee watershed (Flaig and Havens, 1995). Wetland loss inevitably leads to loss of biological, environmental quality and socio-functions such as
flood storage, groundwater recharge, sediment trapping, retention and removal of 

nutrients and pollutants, and wildlife and recreational habitat (Davis and Froend, 1999). 

Among all wetland functions, transport and transformation processes including 
sedimentation, sediment adsorption, nutrient uptake, microbial assimilation and 
transformations, and denitrification may be the most important mechanisms as they are 
responsible for nutrient removal or retention. Fisher and Acreman (2004) investigated 57 
wetlands from around the world and indicated that the majority of wetlands reduced 
nutrient loading and there was little difference in the proportion of wetlands that reduced 
nitrogen (N) to those that reduced P loading. However, they also pointed out that some 
wetlands increased nutrient loading by increasing the loading of soluble N and P species, 
thus potentially driving aquatic eutrophication. Busnardo et al. (1992) researched the 
effect of hydroporiod on nutrient removal efficiency in replicate wetland mesocosms and 
concluded that alternate draining and flooding of sediments (pulsed discharge) increased 
nutrient removal efficiency compared to the continuous-flow “control”. Uusi-Kamppa et 

al. (1997) indicated that in many wetlands the retention of soluble P is much less efficient 
than that of particulate P. Also, waterlogged sediments are known to release P into 
overlying waters (Mortimer, 1941), where it is more likely to be exported from the 
watershed. 

Denitrification, which occurs under anaerobic conditions to release N into the 
atmosphere, is believed by many to be the major mechanism of N loss in wetlands. 
Denitrification rates can be limited by carbon availability and, in this way, vegetation can 
influence denitrification rates indirectly (Broadbent and Clark, 1965). Vegetation may 
also influence nitrification and denitrification by influencing the oxygen concentration of
the wetland substrate within the rhizosphere (Armstrong, 1964) or by providing bacteria which can fix N in root nodules. There is evidence that N removal efficiency is not affected by the length of time the wetland has received N pollution while, in contrast, the ability of a wetland to remove P is known to decline with time (Nichols, 1983; Richardson, 1985).

Wetlands are not stand-alone ecosystems. They impact hydrology, water quality and vegetation dynamics throughout the watershed. Wetlands are characterized by the periodic excess of water inflow over outflow that provides a saturated substrate. The effect of this characteristic is substantial water storage within wetlands and the development of a readily identifiable wetlands flora and fauna which are adapted to periodic anoxic conditions (Bradley and Gilvear, 2000). P loading can alter plant communities through increased plant productivity, tissue P storage, soil P enrichment, and shifts in plant species composition (Davis, 1991; Urban et al., 1993; Chiang et al., 2000). Altered hydrologic regime, caused by water management infrastructure and operations, can also affect the pattern of vegetation communities. Newman et al. (1996) showed that P concentration and water depth are two important driving forces for cattail invasion into the Everglades. Urban et al. (1993) also indicated that a combination of prolonged hydroperiod and P loading stimulates cattail reproduction and encroachment and thus results in the degradation of vegetative habitats and other ecological characteristics in wetlands. Conversely, the physical and physiological characteristics of vegetation influence hydrological response and nutrient cycling. The flora and fauna impact the hydrology of many wetlands in that their incomplete decomposition leads to the progressive development of an organic substrate that itself influences the pattern and
direction of water flow through wetlands and the quantity of water storage (Bradley and Gilvear, 2000). Gurnell et al. (2000) indicated that interception, evapotranspiration, and infiltration processes are particularly heavily influenced by the characteristics and dynamics of the vegetation cover. Many ecologists have recognized that changing vegetation pattern/structure causes feedback that can alter rates of hydrologic processes and nutrient cycling, which, in turn, can cause additional changes in vegetation structure (Lauenroth et al., 1993).

From the above discussion, it is clear that it is critical to understand the role of both BMPs and wetland functions in nutrient removal, retention and storage in order to reduce P loading into Lake Okeechobee. However, it is impractical to test all BMPs for their effectiveness through field experiments. The use of computer models is therefore beneficial because simulation results can not only predict how well a proposed BMP or combined BMPs will reduce P loads, but can also quantitatively evaluate specific hydrologic and biogeochemical processes associated with management activities for BMP design and optimization.

Ecohydrologic modeling that simulates hydrological, biochemical and ecological processes and their interrelations in soil and water bodies has captured the attention of hydrologists and other scientists in recent years. Modeling provides a useful tool for gaining insight into ecohydrological processes and evaluating management practices if model predictions are accurate. Many models have been developed but they are typically linked to the regions where they were developed and tested for a specific purpose and are often limited to specific spatial scales. The unique flatwoods hydrology in the Lake Okeechobee watershed requires the design of a model that can simulate integrated
multidimensional surface and subsurface water, nutrient, and vegetation dynamics at multiple temporal and spatial scales.

Overview of the Coupled Modeling System

For this study, a coupled modeling system that enables the distributed simulation of hydrology, water quality and vegetation dynamics was developed for Okeechobee flatwoods watersheds that incorporate uplands, wetlands, and transition zones located in between these landscapes. The proposed coupled modeling system and the feedback relationships among its submodels are depicted in Figure 1-1. This model system contains a hydrologic submodel as a critical component which simulates precipitation, interception, evapotranspiration, infiltration, water movement within unsaturated soil zones, upward flux, deep seepage, overland flow and groundwater flow. It also includes a submodel for nutrient cycling to simulate the transport and transformation processes for nitrogen and phosphorus. Another necessary part of the model is a vegetation submodel that simulates plant growth dynamics under the combined influence of hydrology, nutrient availability, and land management practices including beef-cattle stocking rates, fire, fertilization, etc.

Figure 1-1. Schematic of the feedback relationships among hydrology, nutrient, and vegetation dynamics in the coupled model system.
The three submodels are coupled in that the interactions and feedbacks between processes of these submodels are simulated together. As outlined in Figure 1-1, plant communities respond to available nutrients and water, which are drivers for plant growth; dynamics of live and standing dead vegetation alter surface water runoff through changes in canopy structure and thus surface roughness. Hydrology in the model responds directly to the vegetation via linkages such as Manning’s roughness coefficient and transpiration losses. Water losses by plants vary with changes in biomass (leaf area index) and physical canopy structure. Availability of water in surface, unsaturated and saturated zone storage is one control on plant growth and mortality. Both surface and subsurface water transport dissolved nutrients, and the soil water conditions affect the biogeochemical processes, while nutrient availability and uptake kinetics can control plant growth. Dead organic matter in different forms is a major source of nutrients.

The coupled model was developed within the Java-based, object-oriented framework of the ACRU2000 model (Campbell et al., 2001; Clark et al., 2001; Kiker and Clark, 2001), an agrohydrological modeling system originally created by Schulze (1989, 1995) in South Africa. The coupled model was developed by adding hydrological components capable of multi-directional spatial simulation of overland flow and lateral groundwater flow, nutrient components capable of multi-directional spatial simulation of conservative solute, nitrogen and phosphorus transport, as well as a new vegetation dynamics simulation model.

**Study Objectives**

The overall purpose of this study was to develop a coupled model system capable of simulating hydrology, nutrient and vegetation dynamics simultaneously for south
Florida flatwoods watersheds that incorporate wetlands, uplands and transition zones.

Specific objectives of this research can be summarized as follows:

- Modify the existing ACRU2000 modeling system to enable the multi-directional spatial simulation of flatwoods hydrology, nutrient and vegetation dynamics.
- Test the accuracy of the modified hydrologic and nutrient models’ performance by comparing with the existing models MIKE SHE and MODFLOW.
- Validate the modified hydrological model by comparing with FHANTM and against the measured data in Dry Lake Dairy #1, Kissimmee River Basin, Florida.
- Calibrate, validate and evaluate the coupled hydrologic and nutrient model using the measured data from Buck Island Ranch, Lake Okeechobee Basin, Florida.
- Test the coupled hydrologic, nutrient, and vegetation model using scenarios based on conditions at Buck Island Ranch, Lake Okeechobee Basin, Florida.
- Investigate the interactions among wetlands hydrology and nutrient dynamics imposed by alternative land management practices and anthropogenic activities in south Florida flatwoods watersheds.

This dissertation is organized into 6 chapters. Chapter 1 briefly introduces the background and objectives of this study, as well as giving an overview of the coupled modeling system; Chapter 2 reviews previous modeling efforts in hydrology, nutrient and vegetation dynamic simulation, and discusses model testing procedures including model calibration, verification, evaluation and sensitivity analysis; Chapter 3 focuses on the development of the multi-directional spatial simulation of the hydrologic model, including a description of model components, algorithms, assumptions, and model testing and validation; Chapter 4 describes the development of the multi-directional spatial nutrient (nitrogen, phosphorus, and conservative solute) transport and transformation model, including model components, algorithms, assumptions and modeling testing and validation; Chapter 5 introduces the vegetation dynamics simulation model, including
model algorithms and testing. Finally, Chapter 6 gives a summary of the results found in this study, conclusions, and recommendations for future work.
CHAPTER 2
LITERATURE REVIEW

Overview of Previous Modeling Efforts

Surface and subsurface water movement serves as a major nutrient transport mechanism, both delivering essential nutrients to the biota and moving excess nutrients to receiving water bodies. The importance of hydrologic transport has been long recognized and considerable effort has been put into creating adequate models for various landscapes (Beven and Kirkby, 1979; Beasley and Huggins, 1980). The complexity of a specific watershed simulation model depends on the temporal and spatial resolution, and on the extent to which important hydrological and biochemical processes are considered (Krysanova et al., 1998). Over the past several decades many models, ranging from lumped conceptual models to semi-distributed models to fully distributed physically-based models, have been developed.

Early examples of lumped hydrologic models are the Stanford Watershed Model (Crawford and Linsley, 1966), the SSARR (Streamflow Synthesis and Reservoir Regulation) model (Rockwood et al., 1972), the Sacramento model (Burnash et al., 1973), the tank model (Sugawara et al., 1976), HEC-1 (Hydrologic Engineering Center, 1981) and the HYMO (Williams and Hann, 1983). In these models, both differential equations based on simplified hydraulic laws and empirical algebraic equations were used for different processes. More recent conceptual models have incorporated soil moisture replenishment, depletion and redistribution for the dynamic variation in areas contributing to direct runoff (Arnold and Fohrer, 2005).
Progress in developing coupled hydrological/water quality models is more evident at the field scale or in small homogeneous watersheds than at large watershed and regional scales. Starting from the early 1970s, non-point source models have been developed in the USA in response to the Clean Water Act. CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980) was developed to simulate the impact of land management on water, sediment, nutrients and pesticides leaving the edge of a field. Subsequently, several field-scale models evolved from the original CREAMS including GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) (Leonard et al., 1987) to simulate groundwater pesticide loadings, EPIC (Erosion-Productivity Impact Calculator) (Williams et al., 1984) to simulate the impact of erosion on crop productivity, and OPUS (Smith, 1992) to estimate the effects of management practices on non-point source pollution.

Spatially-distributed models in larger watersheds represent a more complicated problem (Krysanova et al., 1998). Semi-distributed physically-based hydrologic models have the advantage of a simple model structure and fewer model parameters together with a realistic representation of the watershed hydrologic process. SWAT (Soil and Water Assessment Tool) (Arnold et al., 1993) is a continuous-time distributed simulation watershed model to predict the effects of alternative management decisions on water, sediment and agricultural chemical yields with reasonable accuracy in watersheds and large river basins. SWAT was originally developed from CREAMS to a basin-scale model SWRRB (Arnold et al., 1990), and then combined with the ROTO model (Arnold, 1990) to form the more comprehensive model SWAT. The latest version, SWAT2000, has several significant enhancements that include: bacteria transport routines; urban
routines; Green and Ampt infiltration equation; improved weather generator; ability to read in daily solar radiation, relative humidity, wind speed and potential ET; Muskingum channel routing; and modified dormancy calculations for tropical areas (Arnold and Fohrer, 2005). SWIM (Soil and Water Integrated Model) (Krysanova et al., 1998, 2005), a hybrid of SWAT and MATSALU (Krysanova et al., 1989), is a continuous-time spatially semi-distributed model, which integrates hydrological processes, vegetation growth (agricultural crops and natural vegetation), nutrient cycling (nitrogen and phosphorus) and sediment transport at the river basin scale. AGNPS (Agricultural Non-Point Source pollution model) (Young et al., 1989) was developed to examine water quality as it is affected by soil erosion from agriculture and urban areas during single precipitation events at watershed scale. TOPMODEL (a TOPography based hydrological MODEL) (Beven and Kirkby, 1979) is a variable contributing area conceptual model, in which the major factors affecting runoff generation are the catchment topography and the soil transmissivity that diminishes with depth. ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation) (Beasley and Huggins, 1980) was developed to evaluate the effects of BMPs on surface runoff and sediment loss from agricultural watersheds. The current version of the model, ANSWERS-2000, is a continuous simulation model that was developed in the mid 1990s (Bouraoui and Dillaha, 1996) with the revised nutrient submodels, improved infiltration (Green and Ampt), and new soil moisture and plant growth components to permit long-term continuous simulation.

Another class of models are based on differential equations for conservation of mass, energy and momentum, and are called fully physically-based distributed models.
The spatial distribution of catchment parameters in such models is achieved by representing the basin on a grid network. Examples of physically-based distributed models include MIKE SHE (Refsgaard and Storm, 1995) and MODFLOW (McDonald and Harbaugh, 1988). MIKE SHE is a physically-based, distributed, integrated hydrological and water quality modeling system. It simulates the hydrological cycle including evapotranspiration, overland flow, channel flow, soil water and ground water movement. Related water quality modules include: 1) advection-dispersion, 2) particle tracking, 3) sorption and degradation, 4) geochemistry, 5) biodegradation, and 6) crop yield and nitrogen consumption. This modeling system can be used to predict pollutant loading and transport, pesticide leaching, and outcomes of alternate BMPs on watersheds and their underlying aquifers. MODFLOW is a three-dimensional finite difference groundwater model of the U. S. Geological Survey, which can simulate various stresses to the system such as wells, rivers, drains, head-dependent boundaries, recharge and evapotranspiration. MODFLOW can simulate homogeneous/heterogeneous systems, isotropic/anisotropic media, and steady-state/transient flow.

Model development is often linked to where the model was developed and tested. To simulate the unique flatwoods ecohydrological issues in south Florida watersheds, several models have been developed. These models can be approximately sorted into 3 types according to their functionalities, including (1) hydrologic models such as DRAINMOD (Skaggs, 1980), the weighted implicit finite volume model (Lal et al., 1998), SFWMM (South Florida Water Management Model) (SFWMD, 2005) and NSM (Natural System Model) (SFWMD, 1998); (2) water quality models such as CREAMS-WT (Chemicals, Runoff, and Erosion from Agricultural Management Systems-Water
(Heatwole, 1986), EAAMOD-FIELD (Everglades Agricultural Area MODel-Field) (Bottcher et al., 1998) and FHANTM (Field Hydrologic And Nutrient Transport Model) (Tremwel, 1992; Fraisse and Campbell, 1996, 1997); and (3) ecohydrological models such as ELM (Everglades Landscape Model) (Fitz et al., 2002) and FLATWOODS (Sun et al., 1998).

Some of these models are field-scale, lumped conceptual models, incapable of spatially distributed simulation of ecohydrologic variations. For example, DRAINMOD (Skaggs, 1980) was designed to evaluate the effects of drainage on the water table depth below agricultural fields in the coastal plain of North Carolina where it performed well for the silty-clay soils, but required modifications to improve its ability to predict the outflows from a field with sandy soils (Rogers, 1985). CREAMS-WT (Heatwole, 1986) was modified from CREAMS (Knisel, 1980) to better represent the low phosphorus buffering capacity of sandy soils and the hydrology of flat, sandy, high-water-table flatwoods watersheds. FHANTM (Tremwel, 1992) is based on the DRAINMOD model but was modified to include simulation of phosphorus movement and routing of overland flow. The model was further modified and released as FHANTM 2.0 (Fraisse and Campbell, 1996, 1997) for generalized use in modeling cow/calf operations. This new version incorporates the nutrient component of GLEAMS (Leonard et al., 1987). EAAMOD-FIELD (Bottcher et al., 1998) was developed to assess the effects of different agricultural practices on phosphorus losses from fields in the Everglades Agricultural Area. Zhang et al. (1995) compared CREAMS-WT and FHANTM and concluded that there is little difference in performance of these models in estimating runoff, phosphorus concentration and loads. Zhang et al. (1999) further compared FHANTM, FHANTM
2.0, and EAAMOD-FIELD and concluded EAAMOD-FIELD was the best model to use for the regulatory program because it has the capability of simulating land use changes in the middle of a simulation period and the most potential to be enhanced so that it can be used in the Lake Okeechobee WOD regulatory program. Hendricks (2003) compared FHANTM and EAAMOD, and concluded that EAAMOD predicted water table levels more accurately than FHANTM, and EAAMOD was able to remove the depressional storage water more quickly than FHANTM, allowing EAAMOD’s water table level to respond more quickly when rainfall events subside.

Some of the other models, although they are physically distributed, generally are designed for regional, long-term applications to watersheds at a scale of thousands of square kilometers. Although scalable, performance constraints may impose practical limits on the time and space scales. These models are not intended for local-scale decision-making support because the details of local-scale watersheds may not be sufficiently simulated. For instance, SFWMM (SFWMD, 2005) is a regional-scale computer model that simulates the hydrology and the management of the water resources system from Lake Okeechobee to Florida Bay using a mesh of 2 mile × 2 mile cells. NSM (SFWMD, 2005) uses the same climatic inputs, time step, calibrated model parameters and algorithm as the SFWMM, but it differs from the SFWMM in that it does not simulate the influence of any man-made features and uses estimates of pre-subsidence topography and historical vegetation cover. ELM (Fitz et al., 2002) is a regional-scale, integrated ecological assessment tool designed to understand and predict the landscape response to different water management scenarios in south Florida, USA. In simulating changes to habitat distributions, the ELM dynamically integrates hydrology, water
quality, soils, periphyton, and vegetation in the Everglades region. Due to the computational complexity in the hydrologic modules, the model generally constrains the spatial resolution to 1.0 km² grid cells.

Other models either require relatively small time steps to maintain stability and accuracy, such as the weighted implicit finite-volume model (Lal et al., 1998), or are specially designed for certain application such as FLATWOODS (Sun et al., 1998), which was developed for the cypress wetland-pine upland landscape using a distributed, physically based approach especially useful in the study of forest hydrology.

Vegetation models with different complexities range from simple empirical formulae to complex physiologically-based models. These models differ as a result of the objectives of model development, and hence the required scale and degree of detail and comprehensiveness (Van Ittersum et al., 2003). Over the past decades, a considerable number of vegetation models have been developed to target many different aspects of the terrestrial carbon cycle. At the core of most of these models is a net primary productivity submodel, although many of the mechanisms behind terrestrial productivity are still not properly understood. As a consequence of this, as well as the availability of data and computational capacity at the time of development, models developed to calculate net primary productivity are quite diverse in their approaches (Adams et al. 2003). At one end of the spectrum is the simple, empirically derived, correlation of net primary productivity with air temperature and precipitation used, for example, in the Miami model (Leith, 1975a). At the other end is the detailed simulation of process-oriented, biochemistry used in the Hurley Pasture Model (Thornley and
Cannell, 1997), DSSAT (Jones et al., 2003) and the Wageningen crop models (Van Ittersum et al., 2003).

Several process-based grassland models have been reported such as ELM (Innis, 1978), PAPRAN (Seligman and Van Keulen, 1981), CENTURY (Parton et al., 1987, 1996), ERHYM-II (White, 1987), GEM (Hunt et al., 1991), CCGRASS (Verberne, 1992) and GEMT (Chen and Cougheour, 1994). Compared with these models, the Hurley Pasture Model (Thornley and Cannell, 1997) is more comprehensive in simulating ecosystem processes.

A limited number of previous efforts at modeling vegetation dynamics in south Florida flatwoods watersheds have been reported in the literature. Fitz et al. (1996) developed a processed-oriented General Ecosystem Model (GEM) to capture the response of macrophyte and algae communities to simulated levels of nutrients, water and environment inputs such as light intensity, temperature and fire. The vegetation submodel in SFWMD wetlands model (SFWMD, 1997b) was developed for sawgrass (Cladium) and cattail (Typha) to simulate aboveground (leaves and shoots) and belowground (roots and rhizomes) biomass and nutrient content. This model includes the interactions between light, temperature and nutrients on plant growth and decomposition but it does not consider the effects of hydrology, grazers or other influence on plant growth or survival. Wu et al. (1997) developed SAWCAT using Markov Chain probabilities to simulate vegetation dynamics in wetlands in response to levees, water depth, and phosphorus. The transitional probability model only simulates the number, mean size, and largest size of patches of each vegetation type, but does not simulate biomass production.
Process-oriented vegetation models generally require comprehensive physiological and phenological parameters so that application and testing of these models is difficult in watersheds where little data are available. In this research a simple and generic vegetation dynamics model for simulating the growth dynamics of pasture and wetland grasses found in south Florida watersheds was developed. Details of the vegetation model development are presented in Chapter 5.

**ACRU2000 Modeling System**

The ACRU (Agricultural Catchment Research Unit, v3.00) model was originally developed in FORTRAN by Schulze (1995) in the department of Agricultural Engineering, University of Natal, Pietermaritzburg, South Africa for simulating catchment, forest and wetland hydrology, flood routing, and soil erosion, dam design, irrigation modeling and crop yield modeling within South Africa. Schulze (1995) gives a comprehensive description of ACRU (v3.00) and particular aspects of the model, such as hydrologic sensitivity to climate change, global climate-change and agricultural productivity are described in a range of publications (Schulze et al., 1993; Smithers and Caldecott, 1993; New and Schulze, 1996). ACRU (v3.00) has been enhanced by many additions in response to the need for answers to a range of water-related issues in South Africa and elsewhere (Clark et al., 2001).

ACRU (v3.00) is described as a physical, conceptual model. It is physical in that the hydrological processes are represented as explicitly as possible and conceptual in that the components, relationships and processes in the system are idealized. The hydrologic model in ACRU (v3.00) can operate either as a lumped small catchment model with relatively homogeneous soil and land cover attributes, or as a distributed cell-type model where complex catchments are separated into subcatchments or land segments.
Figure 2-1. General structure of the lumped ACRU (v3.00) model (Schulze, 1995).

In the lumped ACRU (v3.00) model, the core of the model comprises the water budget routines for multiple soil layers on a catchment, the general structure of which is illustrated in Figure 2-1. Water enters the subcatchment as precipitation and/or irrigation. The vegetated or impervious land surface may intercept all or part of the precipitation, and this intercepted water in turn is evaporated back into the atmosphere. For precipitation reaching the soil surface, runoff is calculated using the modified SCS equation, and the balance infiltrates into the topsoil horizon (Clark et al. 2001). Soil water evaporation takes place in the topsoil horizon, and transpiration takes place in those soil horizons that contain roots. Soil water movement takes place between soil horizons. Soil water can percolate from the bottom soil horizon to the groundwater storage. Baseflow is generated and released from the intermediate and groundwater stores as a part of daily surface runoff in this subcatchment. Surface runoff is routed to the subcatchment outlet as a combination of quick flow (storm released into the stream on the
same day as the rainfall events) and delayed storm flow, a surrogate for post storm interflow.

In the distributed ACRU model, a catchment is divided into a set of subcatchments where the lumped model is applied individually throughout the entire simulation time period, then the generated daily runoff from each subcatchment can be convoluted into a runoff hydrograph using the triangular unit hydrograph approach for that subcatchment. The runoff hydrograph from each subcatchment is then routed along the pre-specified pathways to the outlet of the catchment using the Muskingum-Cunge method. No spatial exchange of water flows is considered among subcatchments in ACRU (v3.00). This design may be sufficient to present hydrology in watersheds where topographical gradients dominate water movement and subcatchment hydrology is relatively independent, but is not desirable for low-relief catchments.

To enable code expansion and functionality to meet different needs, ACRU (v3.00) was entirely restructured into ACRU2000 (Campbell et al., 2001; Clark et al., 2001; Kiker and Clark, 2001) within a Java-based, object-oriented framework. In ACRU2000, the internal hydrological modeling features of ACRU (v3.00) were retained but the underlying foundation was changed to allow new features to be developed. The restructured version revised the surface runoff routing algorithm in ACRU (v3.00) by executing each subcatchment every time step and then routing runoff from each subcatchment to the outlet of watershed using the pre-specified pathway before continuing to the next time interval. Additionally, a nutrient module, ACRU-NP (Campbell et al., 2001), patterned after transformation and transport concepts used in the GLEAMS model (Knisel et al. 1993), was added into ACRU2000. Campbell et al.

Figure 2-2. Land segment configuration of the ACRU2000 model (Kiker et al., 2001).

Figure 2-2 shows an example of the land segment configuration of a simulation domain when ACRU2000 runs in a distributed mode. Hydrologic processes, such as rainfall, canopy interception, evapotranspiration, infiltration, runoff, and percolation, etc., simulated in the lumped ACRU model are consistently applied in each land segment when operating the model in a distributed mode. Land segments are connected to one another in a pre-specified pathway, which is used to deliver the runoff from upstream land segments down to outlet of the simulation domain without interactions in land segments along the way. Groundwater is treated as part of surface runoff from each land segment. Physical water exchange is ignored between land segments because water flows bypass downstream land segments. This design may be sufficient to present hydrology in watersheds where topographical gradients dominate water movement and subcatchment hydrology is relatively independent. However, it is not adequate in
simulating south Florida flatwoods hydrology where water movement is primarily
dominated by hydraulic gradients and ecohydrologic variation is spatially interactive in a
significant manner. Furthermore, the nutrient model in ACRU2000, patterned after
transformation and transport concepts used in GLEAMS (Leonard et al. 1987), does not
consider the spatial transport of nutrients through lateral subsurface water movement.

In order to make the ACRU2000 model applicable in south Florida flatwoods
watersheds, modifications were needed to enable multi-directional spatial simulation of
water and nutrients. With the object-oriented design of ACRU2000, it is feasible to add
new modules while retaining the existing capacities of the model. The following
Chapters 3, 4 and 5 describe the details of modifications for hydrology and nutrient
transport simulation, and the addition of the vegetation dynamics model, respectively.

**Model Testing Procedures**

Model testing is a very important part in model development in that it can detect
inappropriate design in model algorithms, increase the model robustness and accuracy
through model calibration and validation, and determine the limitations and constraints of
model application through model evaluation. However, general methodologies related to
model calibration and validation have been subject to considerable discussion and dispute
during the past decades (Refsgaard, 1997).

Distributed models have the capacity to simulate spatial variations. Therefore the
number of parameters and variables are often several orders of magnitude higher than
those required for lumped models of the same area. Lumped and distributed models
should have different requirements with regard to model calibration and validation
procedures. Unfortunately, much attention has been given to specific calibration and
validation procedures for lumped models, whereas very limited attention has so far been
devoted to the more complicated tasks in connection with distributed models (Refsgaard, 1997). The procedure used for model calibration and validation in this study are summarized in the following sections.

**Model Calibration**

Calibration is the process by which model parameters are adjusted to give the best fit between simulated results and observed data at a particulate site. In other words, calibration involves adjusting certain model parameters by systematically comparing simulated results with observations while model structure remains the same. Model calibration is built on the assumption that a well calibrated model enhances its predictive capability by incorporating the best available data and adjusting calibration parameters to obtain a close agreement between model output and historical data.

To calibrate a model adequately, the calibration period should include events that significantly stress the simulation system. Calibration of distributed integrated models is more challenging, as discussed above, due to complex model structures and large parameter sets, and requires calibration over both time and space.

**Model Validation**

Validation is the process by which the calibrated model parameters are used to predict state variables during periods when comparisons can be made to an independent set of historical data, which were not previously used in the calibration process. The purpose of validation is to determine if the model is sufficiently accurate for its application as defined by objectives of the simulation study. The model is said to be validated if its accuracy and predictive capacities in the validation period have been proven to lie within well defined limits that may depend on intended model use.
Sensitivity Analysis

Sensitivity analysis (SA) is the process of varying model input parameters and evaluating how model output changes with such variation (SFWMD, 2005). If a small change in a parameter results in relatively large changes in the model output, the model is said to be sensitive to that parameter. This may mean that the parameter has to be determined very accurately. Prior to accepting the final set of calibrated model parameters, a sensitivity analysis should be performed to determine the relative magnitude of model response to changes in selected parameters.

The most common form of SA is independent parameter perturbation in which parameters are varied individually by a fixed percentage around the base value (Ferreira et al., 1995). An example of this approach is first-order analysis (Hann and Zhang, 1996), in which the first order derivatives in the Taylor series approximation of the output variables are estimated:

\[
s_{ji} = \left( \frac{\partial y_j}{\partial x_i} \right) \approx \frac{y_j(x_i + \Delta x_i) - y_j(x_i)}{\Delta x_i} \quad (i = 1, 2, \cdots, n; j = 1, 2, \cdots, m) \tag{2-1}
\]

in which, \( s_{ji} \) is the sensitivity of output \( y_j \) to the change of parameters \( x_i \); \( y_j (j = 1, 2, \cdots, m) \) are the \( m \) predictions; \( x_i (i = 1, 2, \cdots, n) \) are the \( n \) parameters. These sensitivities \( s_{ji} \) have units and thus are difficult to compare over parameters of interest directly. Thus one can employ normalized or dimensionless sensitivities, Jones and Luyten (1998) used the relative sensitivity, \( r_{s_{ji}} \):
(non-linear effects) may affect the model outputs, even if the output is linear in each parameter. To check for two parameter interactions, second or high order derivatives in the Taylor series approximation must be evaluated. In practice, the computation load to find all possible significant derivatives may be too excessive.

Distributed integrated models are structured to enable simulation of spatial variations in catchment characteristics and thus require more parameters, in principle, than the lumped models. Thus it is necessary to investigate the spatial and temporal sensitivities of input parameters. The first order method as shown in Equation (2-1) and (2-2) was used to conduct the SA on major model outputs including surface runoff, groundwater table depth, and P and N loads. If the output is a time series, the sensitivity is a function of time, which may help to detect the influences of input parameters on extreme values and trends of outputs. If the output is an individual value, an individual sensitivity is calculated, which may help to detect the influences of input parameters on the overall model response. The spatial sensitivities of outputs can be calculated using the same equations when the spatial observation of output variables are available.

The significance of model sensitivity analysis is two-fold in that it provides information on the behavior of model output to input parameters which, in turn, can be used in model calibration; also, it gives insight in establishing priorities related to future data collection efforts. Sensitivity analysis is distinguished from uncertainty analysis in that it is a measure of the relative importance that each input parameter has on the range of simulated outputs. Uncertainty analysis quantifies the confidence in particular output variables given the probability distributions for input parameters. While sensitivity analysis is often limited to parameter sensitivity, uncertainty may be generated by a
number of factors including parameter uncertainty, boundary and initial condition uncertainty, model spatial and temporal resolution, availability and quality of data, and model errors.

**Model Evaluation**

For sake of the model calibration and validation, and the comparison of models, one needs quantitative information to measure model performance compared to observed data or other model predictions. Statistical approaches to quantify the accuracy of model predictions provide standardized measures of model performance although even these methods do not provide completely clear-cut conclusions about the accuracy of model predictions (Ramph, 2004). Given these caveats, the use of several different measures of performance to evaluate a model may present a more complete picture of model performance than any single measure and may allow the user to weight individual results according to their priorities (Ramph, 2004).

**Statistics**

A number of statistics were used to evaluate model results in this study, including model bias, average relative error (RE), root mean square error (RMSE), coefficient of variation (CV), Pearson product-moment correlation coefficient ($R^2$), and Nash-Sutcliffe (NS) coefficient (Nash and Sutcliffe, 1970). Brief overviews of these statistical measures are provided below.

Bias, also called the average error, determines the average deviation of the predicted values from the measured values given N simulated-measured value pairs. As can be seen from Equation (2-3), where $P_i$ is the observed value, $O_i$ is the model-simulated value, and N is the number of observations, bias is calculated as the mean
differences between paired observed and simulated values. Bias values closer to zero indicate better overall model performance.

\[
\text{bias} = \frac{1}{N} \sum_{i=1}^{N} (P_i - O_i) \quad -\infty \leq \text{bias} \leq +\infty \tag{2-3}
\]

The relative error is a unitless, normalized parameter that also quantifies the bias of the predicted values. The arithmetic average relative error (RE) as shown in Equation (2-4) determines if the model overestimates (positive deviation) or underestimates (negative deviation) the measured values, which is most useful for comparing models and data sets (Hession et al., 1994). However, Hession et al. (1994) indicated that the arithmetic average relative error can be significantly influenced by one or two outliers.

\[
\text{RE} = \frac{1}{O} \sum_{i=1}^{N} \frac{(P_i - O_i)}{N} \quad -\infty \leq \text{RE} \leq +\infty \tag{2-4}
\]

The root mean square error (RMSE), or standard deviation/error, provides a direct measure of the error between the model and the observed data (Thomann, 1982) as seen in Equation (2-5). This statistic is used to measure the discrepancy between modeled and observed values, and indicates the overall predictive accuracy of a model. Due to the quadratic term, greater weight is given to larger discrepancies. With this measure, smaller values indicate better model performance (Evans et al., 2003).

\[
\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (P_i - O_i)^2} \quad 0 \leq \text{RMSE} \leq +\infty \tag{2-5}
\]

The RMSE is essentially the overall sum of squares errors normalized to the number of observations (Hession et al., 1994).
The coefficient of variation (Young and Alward, 1983) defines a normalized error as shown in Equation (2-6), which is the RMSE normalized to the overall mean.

\[
CV = \frac{1}{\bar{O}} \sqrt{\frac{1}{N} \sum_{i=1}^{N} (P_i - O_i)^2} \quad -\infty \leq CV \leq \infty
\]  

(2-6)

Using the RMSE, along with the CV, Hedden (1986) suggests that for screening applications a model should be able to replicate observed data within an order of magnitude, and for site-specific applications the predictions should be within a factor of two. In the criterion of within “a factor of two” will be satisfied when the CV value is less than one and the criterion of within “an order of magnitude” will be met when it is less than nine.

The Pearson product-moment correlation coefficient \((R^2)\) value, also called the goodness of fit, is a measure of the degree of linear association between two variables. Depending on the strength of the linear relationship, the \(R^2\) can vary from 0 to 1. The closer \(R^2\) is to 1, the better the regression explains the relationship between simulated and observed. However, it does not explain how close the relationship is to the perfect linear fit \((R^2 = 1)\) between observed and predicted values.

\[
R^2 = \left\{ \frac{\sum_{i=1}^{N} (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum(O_i - \bar{O})^2} \sqrt{\sum(P_i - \bar{P})^2}} \right\}^2 \quad 0 \leq R^2 \leq 1
\]  

(2-7)

Like the \(R^2\) measure described above, Nash-Sutcliffe (NS) coefficient (Nash and Sutcliffe, 1970) is another indicator of goodness-of-fit, and is one of the statistics that have been recommended by the American Society of Civil Engineers (ASCE, 1993) for evaluation of the performance of hydrological models. The NS can vary from 0 to 1,
with 1 indicating a perfect fit. Computationally, the NS could be negative but this becomes rather meaningless as far as interpretation or results are concerned. For NS = 0, the interpretation can be made that the model is predicting no better than using the average of the observed data (ASCE, 1993). The statistics works best when the coefficient of variation for the observed data set is large (ASCE, 1993).

\[
NS = 1 - \frac{\sum_{i=1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2} \quad -\infty \leq NS \leq 1 \quad (2-8)
\]

**Graphic representation**

Graphic representation enables visualizing the relationship between predicted \((P_i)\) and measured \((O_i)\) values and provides a straightforward way to compare the fit between predicted and measured values. Scatterplots and duration curves are two commonly used graphic representation techniques in the hydrological literature.

Scatterplot is a simple method to visualize the relationship between \(P_i\) and \(O_i\) by fitting a regression line between \(P_i\) (Y-axis) and \(O_i\) (X-axis), relative to a line designating a 1:1 relationship. The resulting pattern indicates the type and association/strength of the relationship between predicted and observed values. A positive association would be indicated by upward trend (positive slope) and a negative association would be indicated by a downward trend (negative slope). Or, there might not be any notable association, in which case a scatterplot would not indicate any trends whatsoever. The slope of the regression line and its Y-intercept may provide evidence of systematic error in the model, providing quantities that can be compared across models. A slope of 1.0 with an intercept equal to 0.0 indicates perfect fit of the model predictions.
A duration curve represents the relationship between magnitude and frequency of a variable for a particular watershed providing an estimate of the percentage of time a given variable was equaled or exceeded over a period of time. There are different approaches to generate duration curves for satisfying different purposes. Among these, the flow duration curve (FDC) has widespread application in hydrologic studies such as hydropower, water-supply and irrigation planning. In recent years, duration curves have also been applied in other areas such as load assessment and TMDL development. For this study, the flow and load duration curves were compared for simulated and observed variables.

The basic procedure for generating a duration curve includes: 1) ranking the daily/weekly/annually simulated and measured data separately from highest to lowest for each dataset of interest; 2) calculating percent of days/weeks/years these variables were exceeded (= rank/number of total data points); 3) plotting both simulated and measured data vs. percent of time interval exceeded on the same plot.

Comparison of duration curves between model predictions and observed data provides a direct evaluation of the accuracy of particular flow/load ranges. However, there are some shortcomings of the duration curve method. For example, there is no commonly accepted method to deal with repeated values. Therefore, using duration curves altogether with other statistics is advisable in model evaluation.

No one of the abovementioned model evaluation approaches will be best in all situations. Reviewing several of these measures together will provide a more complete description of model performance (Ramph, 2004). The results should also be viewed in the context of the intended use of the model. Users must decide for themselves what
level of performance is acceptable and, likewise, which approach is most appropriate to their interests.
CHAPTER 3
HYDROLOGIC SIMULATION MODEL

Introduction

In the coupled modeling system, the hydrologic model plays an important role in that it not only simulates hydrologic processes but also provides a framework for the nutrient and vegetation models discussed in Chapters 4 and 5. Therefore, the design and development of the hydrologic model has to take these other models into account.

An example catchment, shown in Figure 3-1A, is discretized into a network (Figure 3-1B) of multiple land segments, each of which is a unique hydrologic unit with varying shape and size depending on land cover, topography, vegetation types and soil types. Each land segment is bordered by either the internal boundaries, which are artificially defined separations between two land segments, and/or the external boundaries, which are the separation between the simulated catchment and its neighboring catchments. A continuous unconfined groundwater system is assumed to underlie the discretized model domain. For each land segment, it is assumed that the soil beneath is laterally homogenous with heterogeneous vertical soil layers that are divided according to natural soil horizons and soil properties. Additionally, soil layers in neighboring land segments have the same number of soil layers of the same thickness, and adjacent soil layers are laterally connected.

A fixed time step of one day is used in the coupled model. The selection of the time step is a tradeoff between time scales required for different model processes and general temporal scales of input data, such as rainfall and evapotranspiration.
An overall flow chart of the coupled modeling system and major model processes included in the model are illustrated in Appendix A. In the natural condition, hydrological processes, together with nutrient and vegetation processes, occur continuously in a simultaneous manner, but in the model these processes are discretized and simulated in a sequential manner within the one day time step. In the model these processes are grouped into vertical and horizontal processes for each land segment according to the flow direction each process describes and whether a process interacts with others in a neighboring land segment. Vertical processes deal with the water movement, nutrient cycling, and vegetation dynamics through the soil profile whereas horizontal processes simulate lateral water movement, nutrient cycling, and vegetation dynamics over the domain and require the simulation of water and nutrient exchange between adjacent land segments. The vertical process group is the basic building block of the model, simulating the temporal dynamics of important hydrological, chemical, and growth processes within one land segment. The horizontal process group is the core of the distributed modeling system in that it spatially connects all land segments in a watershed together through processes such as lateral water movement, nutrient transport,
and biomass expansion. In the coupled model, the vertical processes are executed sequentially throughout the simulation domain for each land segment followed by the horizontal processes across all land segments. Nutrient and vegetation processes are also separately grouped into vertical and horizontal processes. Discussions of these processes are presented in detail in Chapters 4 and 5.

Figure 3-2. Hydrological processes in the modified ACRU2000 hydrologic model.

Hydrologic processes simulated in the modified ACRU2000 model are depicted in Figure 3-2, including rainfall, interception, evapotranspiration (ET), infiltration, soil water redistribution, upward flux, deep seepage, overland flow, canal flow, and groundwater flow. Although some of these processes including rainfall, interception, ET, infiltration, and soil water redistribution existed in the original ACRU2000 model, Martinez (2006) added alternative processes to simulate ET, infiltration, and soil water redistribution and created new processes for deep seepage and upward flux in order to better represent the soil water dynamics for flat, poorly-drained sandy, and high-water-table flatwoods soils in south Florida. Multi-directional spatial simulation of overland
and lateral groundwater flow, and canal flow did not exist in the original ACRU2000 model. Developing algorithms for these processes was the primary purpose of this study.

In the following hydrologic components sections, the methodology used to simulate each process is described, with more detail given to the new overland flow (including canal flow) and lateral groundwater flow processes. Schulze (1995) gave a comprehensive description of the hydrologic processes incorporated into ACRU (v3.00).

The hydrologic model was developed based on the existing hydrologic model in ACRU2000 (Campbell et al., 2001; Clark et al., 2001; Kiker and Clark, 2001) by adding new components and modifying existing components needed for multi-directional spatial simulation, with an emphasis of considering lateral surface and subsurface flow exchange throughout all soil layers between adjacent land segments. Changes were made so that the original model features were retained for other potential applications while enabling new functionality.

The objectives of this Chapter are

- To modify the ACRU2000 hydrologic model to add new hydrologic components that enable multi-directional spatial simulation of overland flow and lateral groundwater flow;
- To analyze the influence of the simulation sequence on simulation results from the modified model;
- To test the ability of the modified model to accurately simulate hydrological processes by comparing with well-accepted models including MIKE SHE (DHI, 2004) and MODFLOW (McDonald and Harbaugh, 1988);
- To test the reliability of the modified model in predicting major hydrologic processes by comparing with the FHANTM model simulations of a field experiment in the Kissimmee River Basin, Florida.

In the following sections, the methodology for each hydrologic component simulated in the modified version of the hydrologic model is described, followed by the
description of boundary and initial conditions required for the model. Then, simulation sequence analyses, hypothetical scenario tests and an application in Dry Lake Dairy #1, Kissimmee River Basin, Florida are presented and discussed and conclusions are drawn. Appendix D lists and describes the added or modified objects. Appendix E lists all newly added variables associated with the coupled modeling system.

**Vertical Hydrologic Components**

**Rainfall**

Rainfall is the fundamental driving force behind most hydrological processes. The success of hydrological simulation studies depends to a large extent on the precision with which the rainfall data are observed temporally and spatially and how they are processed in the model. Several techniques in ACRU (V3.00) are available for estimating aerial rainfall for input files, including

- Driver station method
- ACRU-300 trend surface approach
- Thiessen polygon method
- Inverse distance interpolation technique and
- Spline interpolation technique

The design of input files in the model allows each land segment to have its own daily time series of rainfall depth input. Therefore, the temporal and spatial distribution of rainfall can be differentiated when such spatial rainfall data are available. But within one land segment, or when the model is used in the lumped mode, the rainfall is assumed to have a uniform spatial distribution.

**Canopy Interception**

Canopy interception is calculated as the minimum of the available rainfall and the amount of interception storage capacity available on the intercepting vegetation leaf canopy. The available rainfall first fills available canopy storage, then the remaining
rainfall is assumed to reach the land surface and is available for infiltration or/and surface runoff. If the rainfall is less than or equal to the available canopy storage, all rainfall is intercepted.

**Evapotranspiration**

The calculation of actual evapotranspiration requires three steps including reference potential evapotranspiration (RET), potential evapotranspiration (PET), and actual evapotranspiration (AET). The latter is further separated into soil evaporation and plant transpiration for later use in nutrient uptake discussed in Chapter 4.

The reference evapotranspiration (RET) refers to the maximum evaporation from a short grass surface, or the maximum evaporation from an actively growing alfalfa crop, at least 0.3 m tall, standing erect and covering an extensive area. There are many methods of estimating RET in ACRU (v3.00), ranging from complex physically based equations to simple measurements and even simpler surrogates based on single variables such as temperature:

- The daily United States Weather Bureau Class A pan evaporation.
- The 1948 Penman equation
- Temperature based equations in ACRU (v3.00)
- The Hargreaves and Samani methods (1982 & 1985)
- The Blaney and Criddle (1950) equation
- The Thornthwaite (1948) equation

In addition, Martinez (2006) added the Penman-Monteith grass reference potential evapotranspiration approach (Allen et al. 1998), referred to as FAO56PM in the model. The RET can be calculated separately and input as a time series or calculated directly by the model with required input parameters and data.
For all methods, evapotranspiration is calculated in a top-down approach. First the evaporation demand is applied to intercepted water, next to ponded water on the ground surface, and then to the soil as evaporation and transpiration. The PET for a crop is obtained by multiplying RET with a month-by-month crop coefficient which integrates numerous dynamic processes relating to crop transpiration and soil evaporation.

Two existing AET calculation methods of ACRU (v3.00) have been adapted for use, which calculate AET either as a lumped quantity or by determining soil evaporation and transpiration separately using Ritchie’s method (Ritchie 1972). In addition, a third simple actual evapotranspiration method was added by Martinez (2006).

When calculating evapotranspiration as a lumped quantity, the RET is multiplied by the crop coefficient (V1CAY) to get the PET, then the layer AET within the root zone is calculated as the minimum between the PET and the available water storage (beyond the wilting point) for a specific soil layer. Using an approximate method (Childs and Hanks, 1975), the layer AET is split between soil water evaporation (AE_s) and plant transpiration (AE_t) for use for plant uptake of solutes and nutrients:

\[
AE_s = AET - AE_t
\]  \hspace{1cm} (3-1)

\[
AE_t = \begin{cases} 
0.95AET \times \left( \frac{V1CAY - 0.2}{0.8} \right) & \text{V1CAY} > 0.2 \\
0 & \text{V1CAY} \leq 0.2 
\end{cases}
\]  \hspace{1cm} (3-2)

When using Ritchie’s method to determine evapotranspiration, the potential soil evaporation and plant transpiration are separated as a function of the leaf area index (V1LAI).

\[
PE_s = PET - PE_t
\]  \hspace{1cm} (3-3)
The potential transpiration (PEₜ) is further adjusted by being multiplied by a crop coefficient. The actual plant transpiration can be either equal to maximum transpiration for a given soil layer or be less than maximum transpiration because of a deficiency of available soil water or an excess of soil water. According to Martinez (2006), if the FAO56PM RET is used, the potential evaporation is multiplied by a factor of 1.15 to account for the difference in albedo between bare soil and a vegetated surface as recommended by Allen et al. (1998). The potential soil evaporation (PEₛ) is further adjusted for the percent surface cover by mulch. The soil water evaporation takes place down to a user defined depth of the soil with recommended values ranging from 0.1 to 0.15 m (Allen et al. 1998). According to Ritchie’s method actual evaporation from the soil surface continues at a maximum rate equal to the potential rate (stage 1) until the accumulated soil water evaporation exceeds the stage 1 upper limit. After that, soil water evaporation proceeds at a reduced (stage 2) rate.

The new actual evapotranspiration method that has been added to the model is a simplification to the lumped evapotranspiration method described above. The simplifications include neglecting water stress and the apportionment of evapotranspiration to different layers. Potential evapotranspiration is applied to individual soil layers in the original model according to the fraction of plant roots within that layer. Similarly, the new method applies potential evapotranspiration from the top-most soil layer until the wilting point is reached and then applies the remainder to the layer below until the bottom of the root zone (the last layer containing roots) is reached.

\[
PE_t = \begin{cases} 
(0.7VILAI^{0.5} - 0.21) \times PET & \text{VILAI} < 2.7 \\
0.95PET & \text{VILAI} \geq 2.7
\end{cases}
\]  

(3-4)
Infiltration

Infiltration is a process by which water on the soil surface enters the soil. Considering the high infiltrating capacity of flatwoods soils, the rainfall rate is assumed to be less than the maximum infiltration rate and the water on the ground surface is allowed to infiltrate until the soil profile becomes completely saturated. Thus in the modified ACRU2000, saturated-excess ponding and runoff is simulated. The volume of infiltration is taken as the minimum of the rainfall rate multiplied by grid cell area and time step and the available void space between the water table and land surface. Infiltrating water is moved into the top-most soil layer and is further moved into deeper soil layers through a process discussed below. Water that infiltrates into the soil profile will cause a rise in the water table after any depleted root zone soil moisture is replenished.

Soil Water Redistribution

In ACRU (v3.00), unsaturated soil water redistribution downwards can take place from the top to a subsoil horizon and from the subsoil horizon to groundwater when the soil moisture content in the upper soil horizon is above the field capacity. Upward redistribution, which is similar to capillary movement, takes place from the bottom soil horizon and works up through the soil horizons. If a soil horizon is above porosity then the excess water is moved to the soil horizon above, or in the case of the top soil horizon the surface of the land segment, where it is added to ponded water.

Martinez (2006) created an alternative process specifically for the flatwoods soils. This process redistributes infiltrating water based on the drained-to-equilibrium soil moisture content of each soil layer. According to Martinez (2006), this process has to be turned on after infiltration, net infiltration, new water table depth (if any), and new
drained-to-equilibrium soil moisture contents (if any) have been determined. The process proceeds from the top down, and each soil layer is drained to equilibrium. Then, starting from the bottom-most layer, excess water is moved upwards from the lower to upper layers, or to the ground surface if necessary, to ensure that no layer is above its drained-to-equilibrium water content.

**Upward Flux**

Evapotranspiration depletes the soil moisture content in the root zone and causes an upward gradient between the soil below and the root zone, which induces an upward flux of water within the soil. This depleted root zone has to be replenished first before infiltration occurs to cause a rise in the water table.

The upward flux algorithm was added by Martinez (2006) using an approximate method (Anat et al., 1965) to calculate the maximum steady-state upward flux:

\[
q_{uf} = K_s \left[ 1 + \frac{1.886}{\eta^2 + 1} \right] \left( \frac{d}{h_b} \right)^{-\eta}
\]

where \( q_{uf} \) is the amount of upward flux on a given day [L/T]; \( K_s \) is the saturated hydraulic conductivity of the soil [L/T]; \( d \) is the distance between the water table and the depleted root zone [L]; \( h_b \) is the bubbling pressure head [L]; and \( \eta \) is a function of the pore size distribution index, \( \lambda \), of the Brooks and Corey (1964) model, i.e., \( \eta = 2 + 3\lambda \).

This relationship for upward flux assumes that the soil profile is homogenous. For each soil layer a set of parameters, including \( K_s \), \( h_b \), and \( \lambda \), are input. These parameters can be best obtained by fitting the above equation to a steady-state solution of Richard’s equation for all water table depths below the layer in question. Alternatively, SOILPAR (v2.00) (Acutis and Donatelli, 2003) can be used to estimate these parameters as well.
The amount of upward flux that actually occurs on a given day is the minimum of the maximum value calculated and the amount to which the root zone was depleted (and is now fully replenished by upward flux).

**Deep Seepage**

Deep seepage can occur through a restrictive layer located below the soil profile according to Darcy’s Law. It is calculated as:

\[
q_{ds} = K_s \frac{H_w - H_d}{d}
\]  

(3-6)

where \(q_{ds}\) is the amount of daily deep seepage through the restrictive layer [L/T]; \(K_s\) the restrictive layer saturated hydraulic conductivity [L/T]; \(H_w\) is the height of water table above the restrictive layer [L]; \(H_d\) is the hydraulic head below the restrictive layer [L]; and \(d\) is the thickness of the restrictive layer [L].

**Horizontal Hydrologic Components**

Horizontal hydrologic components including overland flow, lateral groundwater flow and canal flow were newly added into the original ACRU2000 model. The simulation of these components requires water exchange between adjacent land segments. Lateral flow is simulated sequentially, with the simulation sequence determined by the topographic elevations of land segments and the sequence of land segment input files. More details and testing regarding the simulation sequence are discussed in the following section.

The following assumptions were made in the simulation of multi-directional lateral flow:

- For each land segment, only outgoing overland flows are estimated except when inflows occur through external boundaries;
• Overland flows happen only when a positive hydraulic gradient occurs between one land segment and its neighboring land segments, and the ponded water depth in this land segment exceeds its maximum depression storage;

• Potential overland flows are estimated for all neighboring land segments based on hydraulic gradients. If there is insufficient storage to supply all potential outflows, actual outflows are determined through storage apportionment;

• Soil within each land segment is unconfined, thus the hydraulic head is the water level elevation in this land segment above the datum;

• Soils beneath land segments have the same thickness and they are split into the same number of computational soil layers;

• Adjacent computational soil layers in neighboring land segments have the same thickness and are laterally connected.

• Hydraulic gradients are the driving force to transfer groundwater flow laterally in saturated soils;

• From each land segment only outgoing lateral groundwater flows are estimated except when lateral inflows occur through external boundaries;

• Lateral groundwater flows only happen when a positive hydraulic gradient occurs between one land segment and its neighboring land segments;

• Potential groundwater flows are estimated for all neighboring land segments. If there is insufficient storage to supply all potential groundwater flows, actual groundwater flows are decided through storage apportionment.

**Overland Flow**

Appendix B shows a flow chart of overland flow simulation for one source land segment. The potential outgoing overland flows from the source land segment to adjacent land segments are calculated as discussed in the following section and inflows through the external domain boundary are input or extrapolated depending on the actual boundary conditions. Subsequently, a storage check is conducted to guarantee there is enough surface water storage in the source land segment to supply the potential flows. If there is insufficient storage the available water is apportioned according to assumptions discussed in the following section and the detailed algorithm is documented in Appendix
G. External boundary inflows are introduced into boundary land segments each day. The outgoing flows are then transferred to adjacent land segments, which causes a decrease of water storage in the source land segment and an increase of water storage in the adjacent land segment. The whole process described in Figure 3-3 is applied to each land segment in the simulation domain following the simulation sequence generated by the model.

**Overland flow calculation**

The generalized spatial relationship between one land segment and its adjacent land segments is shown in Figure 3-3. Two types of overland flow over internal boundaries are defined in this model:

![Figure 3-3. Configuration of overland flows between source land segment and adjacent land segments. The digit (1~4) of adjacent land segment index indicates the priority to receive the overland flow from source land segment, which is determined by the water elevation of that land segment and smaller water elevations correspond to higher priorities. An adjacent land segment with a larger index has higher priority to receive the overland flow.](image)

**Unstructured boundaries**, where no local obstacles exist to the flow (no singular head losses) and a mean resistance coefficient for a given cross section of the flow can be used. In this case, Manning’s formula is used:
\[ Q_{s,d,i} = \frac{W_{s,d,i} D_{s,d,i} R_{s,d,i}^{2/3} S_{s,d,i}^{1/2}}{n_{s,d,i}} U_m \]  

(3-7)

where subscript \( s \) and \( d \) indicate source and destination land segments and \( i \) the specific adjacent neighbor; \( Q_{s,d,i} \) is the volumetric discharge from source to destination land segments [L$^3$/T]; \( W_{s,d,i} \) is the width of the cross-sectional area between source and destination land segments [L]; \( D_{s,d,i} \) is the water depth of the cross-sectional area between source and destination land segments [L], an average of water depths in both source and destination land segments; \( R_{s,d,i} \) is the hydraulic radius of the flow section between source and destination land segments and it is essentially the average surface water depths [L], roughly equivalent to \( D_{s,d,i} \) for wide, shallow cross-sectional area or streams; \( S_{s,d,i} \) is the water surface slope between source and destination land segments [L/L], it is estimated as:

\[ S_{s,d,i} = \frac{z_s - z_d}{L} \]  

(3-4)

in which, \( z_s \) and \( z_d \) are the water levels of source and destination land segments, respectively [L]; \( L \) is the distance between the centers of source and destination land segments [L]; \( U_m \) is the unit conversion for the Manning formula [L$^{1/3}$/T]; \( n_{s,d,i} \) is the average of Manning’s roughness coefficients of source and destination land segments, which is modified to be a function of sediment type and the interaction of the vegetation height/density and water depth (Fitz et al. 1996). This function creates a dynamic feedback loop between the physical process of flow and the biological process of plant growth (Sklar et al. 2001), which is calculated as:
Figure 3-4. The relationship between Manning's roughness-coefficient \( n \) to water depth and to plant height, both of which change dynamically in the model (Fitz et al., 1996).

\[
n_{s,d,i} = n_{\text{max}} - \left( n_{\text{max}} - n_{\text{min}} \right) \left( 2^{(1-D_d/H_m)} - 1 \right)
\]

where \( n_{\text{max}} \) is the maximum Manning’s roughness coefficient associated with the dynamic vegetation density in the land segment \([L^{1/3}/T]\); \( n_{\text{min}} \) is the minimum Manning’s roughness coefficient for a vegetation-free land segment \([L^{1/3}/T]\); \( D_d \) is the surface water depth \([L]\) and \( H_m \) is the dynamic height of the macrophytes in the land segment \([L]\) (Fitz et al., 1996). Equation (3-5) returns a positive roughness coefficient that ranges from a vegetation-free minimum to a maximum at the point of full plant immersion (Petryk et al., 1975). As water depth increases over that of the macrophyte height, the roughness decreases to an asymptote at the baseline sediment roughness (Nalluri and Judy, 1989). Figure 3-4 shows the relationship between Manning's roughness-coefficient, \( n \), to water depth and to plant height.

**Structured boundaries**, where berms or dikes form a boundary that can be represented by a singular head loss between two land segments. In this case, two kinds of
classical discharge formulae for broad crested weirs (Cunge 1975) are applied according to the following criteria (Cunge 1975):

\[
Q_{s,d,i} = \mu_1 b \sqrt{2g(z_d - z_w)\sqrt{z_d - z_w}} \quad z_s - z_w < \frac{2}{3}(z_d - z_w) \quad (3-6)
\]

- Free flow condition (Free flow weir)

\[
Q_{s,d,i} = \mu_2 b \sqrt{2g(z_s - z_w)\sqrt{z_d - z_s}} \quad z_s - z_w \geq \frac{2}{3}(z_d - z_w) \quad (3-7)
\]

- Submerged flow condition (Drowned weir)

where \(Q_{s,d,i}\) is the volumetric discharge between source and destination land segments over a weir \([L^3/T]\); \(\mu_1\) and \(\mu_2\) are the discharge coefficients; \(b\) is the effective width of the weir \([L]\); \(g\) is the gravitational acceleration \([L^2/T]\); \(z_s\) and \(z_d\) are the water levels of source and destination land segments, respectively \([L]\); \(z_w\) is the elevation of the weir crest \([L]\).

Figure 3-5 shows the relationship between source and destination land segments when a weir exists in between.

**Surface water storage apportionment**

Potential overland flows from one land segment to all its adjacent land segments are calculated separately without taking into account the storage change due to the fluxes that have been already computed. Hence, it is possible that the sum of the potential flows
could exceed surface water storage in the land segment. This situation is especially likely to occur if the time step is large. To avoid this situation, a procedure was developed to limit the actual overland flow to its maximum available volume of storage, hereafter simply called the available volume, which is a portion of the current volumetric water storage on ground surface allocated to a specific neighbor based on the following assumptions:

- The storage apportionment is allocated only to those neighbors that receive the overland flows;
- The current water storage in the land segment is the maximum available volumetric water storage;
- The allocation of the maximum water storage in the land segment is made according to the priority of its neighbors;
- The priority of the neighbors is set up according to the elevation of the water surface boundary between the land segment and its specific neighbor.
- The water surface elevation of the boundary between the land segment and its neighbor is determined by the maximum of the water level or the elevation of the weir crest, whichever exists;
- If a weir exists in between the land segment and its neighbor, the elevation of the weir crest has to be higher than the elevation of the land segment;
- The neighbor with the lowest elevation of boundary has the highest priority for allocation of water storage from the source land segment;
- A neighbor with lower priority is not allocated any water storage until the neighbor with next higher priority is filled to an equivalent water surface elevation, i.e., the two neighbors have equal water surface elevation;
- The available volume for a specific neighbor can not be more than required to equilibrate the water levels of the land segment and this neighbor.

Once the available volumes are determined for all those neighbors receiving potential overland flows from the land segment, each of them is compared with its corresponding pre-estimated potential overland flow. If any potential overland flow exceeds its available volume, then the actual overland flow is set equal to the available
volume. Otherwise, the actual overland flow is equal to its potential value. Details of the assumptions and algorithm for surface water appointment are described in Appendix G.

**Groundwater Flow**

Groundwater flow here refers to lateral groundwater flow which occurs in the saturated soils. Appendix C shows a flow chart of lateral groundwater flow simulation for one land segment. For a source land segment, the potential outgoing lumped lateral groundwater flows and inflows from external domain boundary are calculated, followed by a storage check to guarantee there is sufficient groundwater storage to provide the potential flows from the source land segment. Lumped groundwater flow available for transfer is split into layer flows for the saturated zone in proportion to the layer transmissivity. The layer flows are then transferred to the neighboring land segment. The transmission of layer groundwater flow increases the void space in the soil of the source land segment and decreases that in the neighboring land segments. At the end of
Figure 3-6. Schematic representation of the lateral groundwater flow from the higher head $h_s$ to the lower head $h_d$. (A) and (B) represent the situations without and with overland flow, respectively.
Figure 3-7. Diagram of lateral groundwater flow between two land segments. (A) and (B) represent the generalized situations without and with overland flow, respectively.
simulation, the water table depths are updated for all land segments. The complete process described in Appendix C is applied to each land segment in the simulation domain following the simulation sequence generated by the model.

**Lateral groundwater flow calculation**

Lateral groundwater flow is calculated first in a lumped manner between the saturated zone of source land segment and its adjacent land segments according to Darcy’s law. The lumped flow is then partitioned into the saturated soil layers. Figure 3-6 shows the generalization of lateral flows between two adjacent land segments, in case A (Figure 3-6A) the water table is below the ground surface and case B it is above the ground surface (Figure 3-6B).

The generalization of (A) and (B) in Figure 3-6 is correspondingly illustrated in Figure 3-7(A) and (B). First of all, using Darcy’s Law, the lumped lateral groundwater flow from the source land segment to the destination land segment is estimated

\[
Q_{s,d,i} = K_{s,d,i} S_{s,d,i} W_{s,d,i} H_{s,d,i}
\]

(3-8)

Where subscript s and d indicate source and destination land segments and i the specific neighboring land segment; \(Q_{s,d,i}\) is the lumped lateral groundwater flow from source to destination land segments \([L^3/T]\); \(S_{s,d,i}\) is the hydraulic gradient between source and destination land segments \([L/L]\) and is calculated as

\[
S_{s,d} = \frac{Z_s - Z_d}{L}
\]

(3-9)

in which \(Z_s\) and \(Z_d\) are the groundwater heads of the source and destination land segments, respectively \([L]\); and \(L\) is the distance between the centroids of the source and destination land segments \([L]\); \(K_{s,d,i}\) is the effective horizontal saturated hydraulic conductivity \([L/T]\),
an average of horizontal saturated hydraulic conductivities of the source and destination land segments [L/T]. It is estimated as

\[
K_{s,d,j} = \left( \frac{1}{D_s} \sum_j K_{s,j} b_{s,j} + \frac{1}{D_d} \sum_k K_{d,k} b_{d,k} \right) / 2
\]  

(3-10)

where subscript \(j\) and \(k\) indicate the number of soil layers below the water table of the source and destination land segments, respectively; \(K_{s,j}\) is the saturated horizontal hydraulic conductivity of soil layer \(j\) of source land segment [L/T] and \(K_{d,k}\), that of soil layer \(k\) of destination land segment [L/T]; \(b_{s,j}\) and \(b_{d,k}\) is the thickness of saturated soil of layer \(j\) in source land segment and layer \(k\) in destination land segment [L]; \(D_{s,j}\) and \(D_{d,k}\) is the thickness of saturated soils for source and destination and segments [L]; \(W_{s,d,i}\) is the boundary width of the cross-sectional area between source and destination land segments, perpendicular to the direction of lateral groundwater flow [L]; \(H_{u,d,i}\) is the average of the thickness of saturated soil of source and destination land segments [L],

\[
H_{s,d,i} = \frac{H_s + H_d}{2}
\]  

(3-11)

where \(H_s\) and \(H_d\) are the thickness of saturated soils of the source and destination land segments, respectively [L].

Next, the lateral groundwater flows from source to destination saturated soils are distributed to individual saturated soil layers by the formula

\[
Q_{s,i,j} = Q_{s,d,i} \frac{K_{i,j} b_{i,j}}{\sum_{j=1}^{N} K_{i,j} b_{i,j}}\quad (j = 1, \ldots, N)
\]  

(3-12)

where \(Q_{s,i,j}\) is the layer lateral flow from the saturated soil layer \(j\) of source land segment to the layer \(j\) of destination land segment [L^3/T]; \(K_{i,j}\) is the saturated horizontal hydraulic conductivity of the layer \(j\) of source land segment [L/T]; \(b_{i,j}\) is the thickness of saturated
soil of the layer j of source land segment [L]; N indicates the number of saturated soil layers. In case the water table is located somewhere within a soil layer, the thickness of saturated soil in this layer is the depth from the water table to the bottom of this soil layer.

**Groundwater storage apportionment**

Similar to the procedure of surface water storage apportionment for overland flow, a procedure to check if the sum of the lumped groundwater flows exceeds the available saturated groundwater storage in the source land segment is needed. The available groundwater storage is assumed to be the portion of volumetric water above the field capacity. If the sum of outgoing lumped flows is greater than the available groundwater storage, each lumped groundwater flow is adjusted using a ratio, which is the difference between the sum of outgoing lumped flows and the available volumetric storage to the available volumetric storage. By doing this adjustment, the actual lumped flows are limited to the available storage. Since the groundwater flow is much slower than overland flow this procedure is rarely invoked when the model runs at a daily time step.

**Canal Flow**

The interaction of canals with the simulation domain can occur both through overland flow and lateral groundwater flow depending on the stage of canal and the water level in the domain. When the canal stage is higher than the water level in an adjacent land segment, back flow from the canal into the domain occurs. When the canal stage is lower than the water level in an adjacent land segment, discharge from the domain is released into the canal. Flow between the canal and domain is estimated using the following equations:
\[ q = \frac{WR^{5/3}S^{1/2}}{n} \] \hspace{1cm} \text{Overland flow} \quad (3-13)

\[ q = \text{KWSD} \] \hspace{1cm} \text{Lateral groundwater flow} \quad (3-14)

where \( q \) represents the amount of overland flow to/from the canal in Equation (3-13) and lateral groundwater flow to/from the canal in Equation (3-14) \([L^3/T]\); \( W \) is the width of the land segment-canal boundary \([L]\); \( R \) is the water depth above the ground surface \([L]\); \( S \) is the water slope that is determined by the difference of water level between canal and the adjacent land segment divided by the distance between the centroid of the canal and the centroid of the land segment [-]; \( n \) is the Manning’s roughness coefficient, which is assumed to be the same as the one for the adjacent land segment for this study \([L^{1/3}/T]\); \( K \) is the hydraulic conductivity between the canal and the saturated soils of the adjacent land segment, which is assumed to be the same as the saturated horizontal hydraulic conductivity for the adjacent land segment for this study; and \( D \) is the thickness of the saturated soil profile \([L]\). Currently canal flow is not an individual process in the model but is a built-in routine inside of overland flow and lateral groundwater flow processes.

**Initial and Boundary Conditions**

To ensure the accuracy of the solution of the simulation model, both initial and boundary conditions must be prescribed for the domain being simulated. Initial conditions in the model include water table depth in the soil, ponded water depth if any, and depressional water storage for each land segment. Boundary conditions include boundary inflow, outflow, or fixed head conditions and the description of physical hydraulic structures, levees, fences, and berms, etc. If physical structures exist, geometric information and relevant empirical formula for flows through these structures must be prescribed. Time series of atmospheric variables such as rainfall, temperature,
and potential ET, etc. must also be specified for the desired simulation period. Appendix F shows the input files, required for applications in this dissertation, which contain the initial and boundary conditions.

**Model Testing and Validation**

**Simulation Sequence and Model Performance Accuracy Analysis**

In the modified ACRU2000 hydrologic model, the simulation sequence determines the execution order of land segments. The simulation sequence is generated according to the spatial water flow configuration and the sequence of land segment input files specified in the control menu file (Control.men in Appendix F). The spatial water flow configuration is arranged according to the topographical elevation of each land segment, which specifies the directions of outflow from each land segment and is deterministic once the topography in a simulation domain is specified. However, the sequence of land segment input files in Control.men is arbitrary, for instance, one can specify the sequence from the first land segment to the last one, or its opposite, or other orders. Different simulation sequences can produce different simulation results but the extent to which simulated results, resulting from different simulation sequences, differ from one another needs to be investigated. With this consideration, influence of simulation sequence on model predictions was analyzed. Moreover, the model accuracy is the most important indicator of whether a model is successfully developed. Simulation sequences directly affect the accuracy of the model. Therefore it is necessary to evaluate the model performance accuracy in terms of appropriately selected simulation sequence by comparing the modified model with well-known models.

To investigate the influence of simulation sequence, it is important to understand why the simulated results can be different when different simulation sequences are
specified. As discussed in the introduction section of this Chapter, the vertical and horizontal hydrologic processes are executed in two separate loops in the modified ACRU2000 model. During the vertical processes water is distributed vertically in the soil profile, which results in variation of hydraulic heads between land segments, but each land segment is simulated independently. Horizontal processes transfer surface and subsurface water between neighboring land segments making them interdependent. The simulation of horizontal processes on a particular land segment causes a change of water levels in adjacent land segments. These influences can be propagated to downstream land segments that are simulated later in the simulation sequence. Therefore, it is essential to investigate the difference between different simulation sequence strategies before a decision is made on what would be the most appropriate sequence for the model.

Table 3-1. List of strategies for water transmission and water storage updating for simulation sequence experiments.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Strategies to transfer water and update water storage*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>Water transferred in lateral processes is not available for transmission to downstream land segments and also does not cause head changes until the end of the day when all land segments have been simulated.</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>Water transferred in lateral processes is available for transmission to downstream land segments but does not cause head changes until the end of the day when all land segments have been simulated.</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>Water transferred in lateral processes is available for transmission to downstream land segments and also causes heads changes immediately.</td>
</tr>
</tbody>
</table>

* Water storage either on the ground surface or in the saturated soil layers.

Three experiments, corresponding to different strategies for water transmission and storage updating, are listed in Table 3-1. These experiments were conducted based on two hypothetical scenarios, a flat rectangular plane and an axisymmetric domain. To further evaluate the model performance accuracy, the simulated results from the first scenario were compared with the two-dimensional overland flow model in MIKE SHE.
(DHI, 2004) and the results from the second scenario were compared with the three-dimensional groundwater flow models in both MIKE SHE (DHI, 2004) and MODFLOW (McDonald and Harbaugh, 1996).

**Case 1: Overland flow along a flat rectangular plane**

A flat rectangular plane with a size of 100 m × 2000 m was used to test the influence of simulation sequence on overland flow in the modified ACRU2000 hydrologic model. The plane was divided into 20 land segments, each with a size of 100 m × 100 m as shown in Figure 3-8. An initial head of 0.5 m was assigned for land segment 1 (hereafter LS1), 0.4 m for LS2, 0.3 m for LS3, 0.2 m for LS4, 0.1 m for LS5, and 0.0 m for the rest of land segments so that all with a mild water slope (= 0.001 m/m) was created from LS1 through LS5 to drive water propagation from the left to the right of the plane. A closed boundary condition was assumed and a 30-day period was simulated.

The modified ACRU2000 model was first run for the three experiments (Table 3-1) from LS1 to LS20, and then the model was run again for the same experiments but with an opposite sequence, from LS20 to LS1.

![Figure 3-8. A rectangular plane with 20 land segments (arrow indicates water movement direction and digits assigned in each grid cell indicate the number for each land segment).](image)

The simulated surface water depths from the three experiments each using the two simulation sequences are compared in Figure 3-9. For Experiment 1, the model produced identical results for both simulation sequences. This is because the hydraulic gradients over the domain do not change during one time step for this experiment and water
transmission and water storage updates do not happen until the end of each time step when all land segments have been simulated. Significant difference in surface water depths between simulation sequences is observed in Experiment 2. Water moves faster when the simulation order is consistent with the flow direction (from LS1 to LS20) and it moves slower when the simulation order is against the flow direction (from LS20 to LS1). In this experiment the water gradient remains constant during one time step, however the water storages are updated within the time step which causes more water to move downstream during the time step if it is available. Differences in simulated water depths between simulation sequences also occur in Experiment 3 but they are not as significant as those in Experiment 2. When the water slopes within the domain get smaller (i.e. on days 20 and 30), the differences between both simulation sequences diminish. These comparisons show that the simulation order does cause a difference in surface water depths but the magnitude of the difference depends on the gradient and storage update strategies.

Figure 3-10 compares the simulated surface water depths along the domain from the three experiments with those from MIKE SHE’s overland flow model for the simulation sequence from LS1 to LS20. On Day 2, there is a good agreement between these two models for all three experiments. On day 10 and 20, the modified ACRU2000 hydrologic model moves water faster than MIKE SHE’s overland flow model for all three experiments, although the models agree with each other fairly well on timing and trends. Statistics calculated by using the predictions from MIKE SHE’s model as observed values, and the predictions from the modified ACRU2000 model as the simulated values quantify the differences. As shown in Table 3-2, all statistics including
bias, RE, RMSE, CV, $R^2$ and NS are very close to one another among the three experiments, especially those for bias and RE. For all selected days, Experiment 1 is better than Experiments 2 and 3 for the statistics RMSE, CV, $R^2$ and NS although the differences are not that significant. These graphic and statistical comparisons indicate that for all three experiments the ACRU2000 model compares reasonably well with MIKE SHE even though where significantly different methodologies and time steps are used.

Table 3-2. Statistics for the surface water depths predicted by the modified ACRU2000 model and MIKE SHE for the three experiments with the same simulation sequence.

<table>
<thead>
<tr>
<th>Statistics* (units)</th>
<th>bias (m)</th>
<th>RE (-)</th>
<th>RMSE (m)</th>
<th>CV (-)</th>
<th>$R^2$ (-)</th>
<th>NS (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0057</td>
<td>0.0171</td>
<td>0.9984</td>
<td>0.9984</td>
</tr>
<tr>
<td>Day 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.0000</td>
<td>0.0001</td>
<td>0.0148</td>
<td>0.0443</td>
<td>0.9899</td>
<td>0.9893</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>0.0000</td>
<td>0.0001</td>
<td>0.0087</td>
<td>0.0261</td>
<td>0.9976</td>
<td>0.9963</td>
</tr>
<tr>
<td>Day 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 1</td>
<td>0.0000</td>
<td>0.0001</td>
<td>0.0133</td>
<td>0.0396</td>
<td>0.9935</td>
<td>0.9874</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.0000</td>
<td>0.0001</td>
<td>0.0283</td>
<td>0.0845</td>
<td>0.9610</td>
<td>0.9425</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0372</td>
<td>0.1108</td>
<td>0.9604</td>
<td>0.9011</td>
</tr>
<tr>
<td>Day 20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 1</td>
<td>0.0000</td>
<td>-0.0001</td>
<td>0.0239</td>
<td>0.0714</td>
<td>0.9749</td>
<td>0.9490</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0402</td>
<td>0.1197</td>
<td>0.9399</td>
<td>0.8564</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>0.0000</td>
<td>-0.0001</td>
<td>0.0495</td>
<td>0.1476</td>
<td>0.9182</td>
<td>0.7818</td>
</tr>
</tbody>
</table>

*Statistics were calculated by assuming the predictions from MIKE SHE as the observed values while the predictions from the modified ACRU2000 as the predicted values. All three experiments were conducted with the same simulation sequence from LS1 to LS20.

However, this rectangular plane domain is quite special in that each land segment only has water exchange with either upstream or downstream land segments and the simulation sequence either is consistent with or against the flow direction. To further investigate the influence of simulation sequences, a more complicated domain was used in the following experiment.
Comparison of Surface Water Depths over Land Segments for Experiment 1

Comparison of Surface Water Depths over Land Segments for Experiment 2

Comparison of Surface Water Depths over Land Segments for Experiment 3

Figure 3-9. Comparisons of the simulated surface water depth from the modified ACRU2000 model on the three experiments between two opposite simulation sequences.
Comparison of Surface Water Depths over Land Segments on Day 2

Comparison of Surface Water Depths over Land Segments on Day 10

Comparison of Surface Water Depths over Land Segments on Day 20

Figure 3-10. Comparisons of the simulated surface water depths between the MIKE SHE’s overland flow model and the modified ACRU2000 hydrologic model on the three experiments with the simulation sequence from LS1 to LS20.
Case 2: Overland and groundwater flow over an axisymmetric domain

An axisymmetric domain with its 2D and 3D gridded discretization as shown in Figure 3-11 was used to test the influence of simulation sequence on both overland and groundwater flows in the modified ACRU2000 model. The domain, with a size of 600 m × 600 m, is composed of 100 meter square grid cells, each of which is 2 m in depth. Four equal-thickness computational soil layers with homogenous soil properties for each soil layer were assumed for each land segment. The surface elevation for each land segment was set to 10 m. Homogeneous hydrologic and physical characteristics were assumed for each land segment including the Manning’s roughness coefficient (= 0.1 m$^{1/3}$/s), soil layer thickness (= 0.5 m), horizontal/vertical hydraulic conductivity (= 0.0000444 m/s), specific yield (= 0.25), and storage coefficient (= 0.00005 m$^{-1}$). An initial water depth of 0.5 m was assigned to the central four land segments, 0.25 m to the land segments surrounding the central ones, and 0.0 m to the rest of land segments for the overland flow simulation in this scenario. For the groundwater flow simulations, the previous setting for initial water levels in each land segment was lowered by a depth of 1.5 m so that no surface water movement would occur. A closed boundary condition was assumed. A 30-day simulation period was used for the overland flow simulation and a 2-year simulation period for the groundwater flow simulation.

The objectives for this case study were to investigate the difference in simulated results for the three experiments (Table 3-1) in a more complicated domain where land segments may interact spatially with one another in multiple directions, and compare the simulated surface water depths with those from MIKE SHE (DHI, 2004) and groundwater table depths with those from MIKE SHE (DHI, 2004) and MODFLOW (McDonald and Harbaugh, 1988). A simulation sequence, which transfers water from the
center to boundary of the domain symmetrically following the flow direction, was specified. An hourly time step was used for the 2D overland flow model in MIKE SHE, a varying time step ranging from 2 to 12 hours for the 3D groundwater flow model in MIKE SHE, and a daily time step for the groundwater flow model in MODFLOW and the modified ACRU2000 model. The model was run separately with different initial water level settings so that both surface overland flow and groundwater flow can be investigated individually.

For the overland flow simulation, the simulated surface water depths from LS19, LS20, LS21, LS25, LS26, and LS31 were selected for analysis because of the axisymmetric distribution of water depths over the domain. For each selected land segment, the simulated water depths from the three experiments were compared with those from MIKE SHE’s overland flow model as shown in Figure 3-12. Similar to the conclusions drawn from Case 1, the comparisons from all three experiments in all selected land segments indicate that water moves slightly faster in the modified ACRU2000 model than in MIKE SHE. The results from Experiments 1 and 2 show
Figure 3-12. Comparisons of simulated water depths of the selected land segments between the modified ACRU2000 model and the MIKE SHE’s overland flow model for the three experiments.
Figure 3-12. Continued.
Table 3-3. Statistics for the surface water depths predicted by the modified ACRU2000 model and MIKE SHE for the three experiments.

<table>
<thead>
<tr>
<th>Statistics*</th>
<th>bias</th>
<th>RE</th>
<th>RMSE</th>
<th>CV</th>
<th>R^2</th>
<th>NS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(units)</td>
<td>(m)</td>
<td>(-)</td>
<td>(m)</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>-0.0015</td>
<td>-0.0111</td>
<td>0.0078</td>
<td>0.0589</td>
<td>0.9139</td>
<td>0.9047</td>
</tr>
<tr>
<td>LS19</td>
<td>0.0000</td>
<td>0.0002</td>
<td>0.0121</td>
<td>0.0909</td>
<td>0.8028</td>
<td>0.7726</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.0011</td>
<td>0.0082</td>
<td>0.0068</td>
<td>0.0512</td>
<td>0.9315</td>
<td>0.9278</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>-0.0138</td>
<td>-0.0861</td>
<td>0.0175</td>
<td>0.1091</td>
<td>0.8224</td>
<td>0.3598</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>-0.0164</td>
<td>-0.1022</td>
<td>0.0205</td>
<td>0.1281</td>
<td>0.7208</td>
<td>0.1187</td>
</tr>
<tr>
<td>LS20</td>
<td>0.0000</td>
<td>0.0002</td>
<td>0.0121</td>
<td>0.0909</td>
<td>0.8028</td>
<td>0.7726</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.0011</td>
<td>0.0082</td>
<td>0.0068</td>
<td>0.0512</td>
<td>0.9315</td>
<td>0.9278</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>-0.0138</td>
<td>-0.0861</td>
<td>0.0175</td>
<td>0.1091</td>
<td>0.8224</td>
<td>0.3598</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>-0.0225</td>
<td>-0.1207</td>
<td>0.0292</td>
<td>0.1563</td>
<td>0.9524</td>
<td>0.8059</td>
</tr>
<tr>
<td>LS21</td>
<td>-0.0253</td>
<td>-0.1353</td>
<td>0.0322</td>
<td>0.1725</td>
<td>0.9393</td>
<td>0.7637</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>-0.0265</td>
<td>-0.1419</td>
<td>0.0335</td>
<td>0.1794</td>
<td>0.9319</td>
<td>0.7445</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>-0.0265</td>
<td>-0.1419</td>
<td>0.0335</td>
<td>0.1794</td>
<td>0.9319</td>
<td>0.7445</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>0.0128</td>
<td>0.1092</td>
<td>0.0214</td>
<td>0.1832</td>
<td>0.7289</td>
<td>0.3180</td>
</tr>
<tr>
<td>LS25</td>
<td>0.0141</td>
<td>0.1205</td>
<td>0.0232</td>
<td>0.1986</td>
<td>0.6855</td>
<td>0.1983</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.0141</td>
<td>0.1205</td>
<td>0.0232</td>
<td>0.1986</td>
<td>0.6855</td>
<td>0.1983</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>0.0141</td>
<td>0.1204</td>
<td>0.0159</td>
<td>0.1358</td>
<td>0.9322</td>
<td>0.6249</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>0.0015</td>
<td>0.0105</td>
<td>0.0221</td>
<td>0.1546</td>
<td>0.4450</td>
<td>-0.1851</td>
</tr>
<tr>
<td>LS26</td>
<td>0.0015</td>
<td>0.0102</td>
<td>0.0210</td>
<td>0.1470</td>
<td>0.4703</td>
<td>-0.0715</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>-0.0028</td>
<td>-0.0193</td>
<td>0.0092</td>
<td>0.0642</td>
<td>0.8471</td>
<td>0.7955</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>0.0256</td>
<td>0.2555</td>
<td>0.0328</td>
<td>0.3271</td>
<td>0.7377</td>
<td>-0.1002</td>
</tr>
<tr>
<td>LS31</td>
<td>0.0276</td>
<td>0.2759</td>
<td>0.0355</td>
<td>0.3542</td>
<td>0.6569</td>
<td>-0.2900</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.0290</td>
<td>0.2895</td>
<td>0.0331</td>
<td>0.3307</td>
<td>0.7684</td>
<td>-0.1246</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>0.0290</td>
<td>0.2895</td>
<td>0.0331</td>
<td>0.3307</td>
<td>0.7684</td>
<td>-0.1246</td>
</tr>
</tbody>
</table>

* Statistics were calculated by assuming the predictions from MIKE SHE as the observed values while the predictions from the modified ACRU2000 model as the simulated values. All three experiments were performed with the same simulation sequence.

fluctuations at early times of simulation but eventually trend to the results from Experiment 3 in which the curve of predicted water depths appears smooth. However, the differences among the three experiments seem to be not that significant. Both models agree with each other fairly well on timing and trends.

Table 3-3 shows the statistics that were calculated by using the predictions from MIKE SHE as the “observed” values. The statistics indicate that the model generally produced better predictions in Experiment 3 than in the other two experiments with smaller RMSE and CV values and larger R^2 and NS values in four selected land segments (LS19, LS20, LS25 and LS26) and similar predictions in LS21 and LS31 with the other
two Experiments. It should be noted that slightly larger values of bias and RE are observed in Experiment 3 in some of these land segments. Overall, it was concluded that the modified ACRU2000 model performed better in Experiment 3 for this scenario and thus Experiment 3 is the most appropriate strategy for producing reasonable surface water depths for this axisymmetric domain. To further visualize the comparison of simulated results for Experiment 3, Figure 3-13 displays a time series comparison of surface water depths for all selected land segments for these two models.

Figure 3-13. Comparisons of the simulated water depths of the selected land segments between the modified ACRU2000 and MIKE SHE’s overland flow model for Experiment 3.
A groundwater simulation test was made by changing initial water levels as discussed earlier. Similar to the above overland flow simulation, the simulated groundwater table depths also display an axisymmetric distribution pattern over the domain. Therefore the simulated water table depths from LS19, LS20, LS21, LS25, LS26, and LS31 were used to compare with the MIKE SHE’s predictions for all three experiments as shown in Figure 3-14. From this figure, it is fairly difficult to tell the difference among the simulated results from the three experiments for they all have very similar predictions for all selected land segments. Interestingly, the ACRU results for the three experiments are consistently located in between the predictions from MIKE SHE and MODFLOW for all selected land segments, although these results agree with MIKE SHE’s predictions better in LS19, LS20, LS25, LS26, and LS31 and with MODFLOW’s predictions better in LS21. The comparisons also reveal that the ACRU2000 groundwater movement is slightly faster than MIKE SHE and a little bit slower than MODFLOW. The difference in predicted groundwater table depths between the modified ACRU2000 model and the other two models seems larger in the central land segments (LS20, LS21, and LS26) than it appears in the land segments along the boundary (LS19, LS25, and LS31). This could result from the larger hydraulic gradient variations between the central land segments and milder gradients between the boundary land segments. In general, three models agree with one another on timing and tendency quite well.

Table 3-4 shows the statistics that were calculated by using the predictions from MIKE SHE and MODFLOW as the “observed” values for the three experiments for all selected land segments. Over all selected land segments, there are no significant
differences among the bias, RE, RMSE, CV, and \( R^2 \) values. However, some systematic differences in the NS values are noticed between the predictions from MIKE SHE and MODFLOW as the “observed” values: excellent NS values close to 1 for LS19, LS25, and LS31, fairly good NS values for LS21 and LS26 and poor NS values were obtained for LS20 when comparing to MIKE SHE’s predictions. On the other hand, the NS values vary gradually for all selected land segment from excellent to fairly good when comparing to MODFLOW’s predictions. Thus it is difficult to differentiate the model performance among the three experiments and thus conclude unequivocally which experiment provides the most appropriate strategy.

From the previous case studies for two different hypothetical scenarios, it can be concluded that the simulation sequence affects the simulation results, but not very significantly. Thus picking a simulation sequence that follows the flow directions determined by the topography on the ground surface is reasonable. Moreover, among the three alternative water transmission and water storage updating strategies, Experiment 3 appears to be the most appropriate one for reasonable simulation of overland flow but no significant difference was observed in simulation of groundwater flow. By comparing to results from MIKE SHE and MODFLOW, the modified ACRU2000 model has been shown to simulate hydrology reasonably well.
Figure 3-14. Comparisons of the groundwater table depths at the selected land segments between and the modified ACRU2000 hydrologic model and MIKE SHE’s groundwater flow model for the three experiments.
Groundwater Table Depths over Time at Land Segment 25

Groundwater Table Depths over Time at Land Segment 26

Groundwater Table Depths over Time at Land Segment 31

Figure 3-14. Continued.
Table 3-4. Statistics for the simulated groundwater table depths by the modified ACRU2000 model, MIKE SHE, and MODFLOW for the three experiments with the same simulation sequence.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>-0.0010</td>
<td>0.0118</td>
<td>0.0077</td>
<td>0.019</td>
<td>0.014</td>
<td>0.020</td>
<td>0.9982</td>
<td>0.9932</td>
<td>0.9968</td>
<td>0.8774</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 2</td>
<td>-0.0012</td>
<td>0.0116</td>
<td>-0.0009</td>
<td>0.0082</td>
<td>0.0021</td>
<td>0.0120</td>
<td>0.982</td>
<td>0.9932</td>
<td>0.9963</td>
<td>0.8825</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 3</td>
<td>-0.0012</td>
<td>0.0116</td>
<td>-0.0008</td>
<td>0.0082</td>
<td>0.0021</td>
<td>0.0121</td>
<td>0.982</td>
<td>0.9932</td>
<td>0.9964</td>
<td>0.8808</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 1</td>
<td>0.0113</td>
<td>-0.0163</td>
<td>0.0090</td>
<td>-0.0127</td>
<td>0.0140</td>
<td>0.0173</td>
<td>0.979</td>
<td>0.9774</td>
<td>-1.3373</td>
<td>0.3915</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.0111</td>
<td>-0.0166</td>
<td>0.0088</td>
<td>-0.0129</td>
<td>0.0139</td>
<td>0.0175</td>
<td>0.979</td>
<td>0.9778</td>
<td>-1.2802</td>
<td>0.3763</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 3</td>
<td>0.0115</td>
<td>-0.0162</td>
<td>0.0091</td>
<td>-0.0126</td>
<td>0.0142</td>
<td>0.0171</td>
<td>0.977</td>
<td>0.9782</td>
<td>-1.3765</td>
<td>0.4006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 1</td>
<td>0.0289</td>
<td>-0.0181</td>
<td>0.0258</td>
<td>-0.0155</td>
<td>0.0323</td>
<td>0.0205</td>
<td>0.988</td>
<td>0.9988</td>
<td>0.5957</td>
<td>0.9247</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.0288</td>
<td>-0.0182</td>
<td>0.0257</td>
<td>-0.0156</td>
<td>0.0322</td>
<td>0.0206</td>
<td>0.987</td>
<td>0.9987</td>
<td>0.5990</td>
<td>0.9237</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 3</td>
<td>0.0293</td>
<td>-0.0177</td>
<td>0.0261</td>
<td>-0.0152</td>
<td>0.0326</td>
<td>0.0203</td>
<td>0.987</td>
<td>0.9987</td>
<td>0.5890</td>
<td>0.9265</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 1</td>
<td>-0.0004</td>
<td>0.0101</td>
<td>-0.0003</td>
<td>0.0070</td>
<td>0.0010</td>
<td>0.0104</td>
<td>0.9992</td>
<td>0.9987</td>
<td>0.9984</td>
<td>0.8414</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 2</td>
<td>-0.0007</td>
<td>0.0098</td>
<td>-0.0005</td>
<td>0.0068</td>
<td>0.0011</td>
<td>0.0102</td>
<td>0.992</td>
<td>0.9987</td>
<td>0.9980</td>
<td>0.8482</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 3</td>
<td>-0.0006</td>
<td>0.0099</td>
<td>-0.0004</td>
<td>0.0069</td>
<td>0.0011</td>
<td>0.0103</td>
<td>0.9993</td>
<td>0.9987</td>
<td>0.9981</td>
<td>0.8456</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 1</td>
<td>0.0104</td>
<td>-0.0155</td>
<td>0.0080</td>
<td>-0.0116</td>
<td>0.0113</td>
<td>0.0160</td>
<td>0.986</td>
<td>0.9808</td>
<td>0.7156</td>
<td>0.6420</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 2</td>
<td>0.0102</td>
<td>-0.0157</td>
<td>0.0078</td>
<td>-0.0117</td>
<td>0.0111</td>
<td>0.0162</td>
<td>0.986</td>
<td>0.9806</td>
<td>0.7255</td>
<td>0.6328</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 3</td>
<td>0.0106</td>
<td>-0.0153</td>
<td>0.0081</td>
<td>-0.0115</td>
<td>0.0114</td>
<td>0.0158</td>
<td>0.986</td>
<td>0.9805</td>
<td>0.7110</td>
<td>0.6473</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 1</td>
<td>-0.0015</td>
<td>0.0130</td>
<td>-0.0010</td>
<td>0.0089</td>
<td>0.0017</td>
<td>0.0150</td>
<td>0.996</td>
<td>0.9937</td>
<td>0.9840</td>
<td>0.5285</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 2</td>
<td>-0.0016</td>
<td>0.0129</td>
<td>-0.0011</td>
<td>0.0088</td>
<td>0.0019</td>
<td>0.0149</td>
<td>0.995</td>
<td>0.9940</td>
<td>0.9810</td>
<td>0.5382</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment 3</td>
<td>-0.0016</td>
<td>0.0129</td>
<td>-0.0011</td>
<td>0.0088</td>
<td>0.0019</td>
<td>0.0149</td>
<td>0.995</td>
<td>0.9940</td>
<td>0.9810</td>
<td>0.5383</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*a statistics were calculated using the predictions by MIKE SHE as the observed values and the predictions by the modified model as the simulated values.

b statistics were calculated using the predictions by MODFLOW as the observed values and the predictions by the modified model as the simulated values.
Application at Dry Lake Dairy #1, Kissimmee River Basin, Florida

Site description

The Dry Lake Dairy #1 is an agricultural pasture site located within the lower Kissimmee River and Taylor Creek-Nubbin Slough Basins (Figure 3-15). The site is located on Immokalee soil with surface depressions and little slope, thus the pasture often becomes flooded during the rainy season. The spodic horizon for Immokalee fine sand typically occurs at approximately 90 cm and averages 50 cm in thickness. The upper zone of the spodic horizon is black and weakly-cemented, while the lower zone is a mottled, dark reddish brown and is even more weakly cemented than the upper layer. During the wet season, the water table stands near or at the surface for short periods and recedes to below 120 cm during the dry season (Capece, 1994).

Figure 3-15. Location of Dry Lake Dairy #1 site (Capece, 1994).
A topographic map of the Dry Lake Dairy #1 site is shown in Figure 3-16. As observed, a low, broad berm isolated the study area from the rest of the pasture. The berm varied in height from 45 to 60 cm above ground surface and was approximately 5 m across at its base. The total area contained within this berm was 5.9 ha (Campbell et al., 1995). The flume station was located approximately 200 m from the weather station. Two supplemental wells were constructed at the weather station for continuous water-
table monitoring. Water-table depth in one well near the flume also was continuously monitored by the flume datalogger (Campbell et al., 1995). A shallow collection ditch paralleled the perimeter berm for approximately one third of its length nearest the flume station. This V-shaped collection ditch was grassed and was less than 30 cm deep and approximately 3 m wide (Campbell et al., 1995). The constructed collection ditch discharged into a trapezoidal flow measurement flume with a maximum capacity of 7.1 cfs (200 l/s). A total of 69 well stations were established on this site. Each well station was composed of two or three wells of different depths.

Weather, runoff and groundwater quality measurements were obtained at the Dry Lake Dairy #1 site to provide information concerning water and P movement in flat, sandy, high-water-table soils. Summary data for annual rainfall, ET, and observed runoff are listed in Table 3-5. These data indicate that years 1989 and 1990 were dry years when compared to year 1991 with less rainfall and more ET. Year 1991 was relatively wet with relatively more rainfall. A simple water budget in the last column of Table 3-5 shows year 1989 is the driest, year 1990 ranks the second, and year 1991 is the wettest among the three years.

Table 3-5. Summary of annual water budget on Dry Lake Dairy #1 sitea.

<table>
<thead>
<tr>
<th>Years</th>
<th>Rainfall (R) (cm)</th>
<th>Runoff (RO) (cm)</th>
<th>ET (cm)</th>
<th>100×(ET+RO-R)/R (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989 (April-December)</td>
<td>88.66</td>
<td>5.15</td>
<td>91.37</td>
<td>8.87</td>
</tr>
<tr>
<td>1990</td>
<td>117.47</td>
<td>25.71</td>
<td>100.30</td>
<td>7.27</td>
</tr>
<tr>
<td>1991</td>
<td>133.00</td>
<td>44.29</td>
<td>92.18</td>
<td>2.61</td>
</tr>
<tr>
<td>Total</td>
<td>339.13</td>
<td>75.14</td>
<td>283.85</td>
<td>5.86</td>
</tr>
</tbody>
</table>

aData from Tremwel (1992).

The purpose of this application was to validate the modified ACRU2000 model by comparing with the lumped FHANTM model (Tremwel, 1992), which was applied in the Dry Lake Dairy #1 site in 1992. For the modified ACRU2000 simulation, the Dry Lake
Dairy #1 site was divided into 4 land segments, each with identical hydrologic properties and soil layers since no spatially distributed data were available. The discharge from the site through the flume was estimated using the empirical formula (Tremwel, 1992)

\[ Q = 3.282156h^{2.5} + 0.508387h^{1.5} + 0.121409h^{0.5} \]  

(3-10)

in which \( Q \) is the discharge in cubic feet per second and \( h \) is the surface water depth in feet. The measured rainfall, pre-calculated potential ET, and temperature from Tremwel (1992) were used as the time series input and were applied uniformly for each land segment. Some input such as soil properties (field capacity, soil porosity, wilting point, and hydraulic conductivity) as shown in Table 3-6 were adapted from the calibrated parameters by Tremwel (1992) for FHANTM and the rest of input were estimated. No deep seepage process was considered in the test. No calibration was performed for the modified ACRU2000 model.

The simulation period for this validation test was from April 1989 through December 1991. The model was run throughout the whole simulation period and the simulated results for surface runoff and groundwater table were compared with those from FHANTM, for both the calibration period (April 1, 1989 to August 31, 1990) and the verification period (September 1, 1990 to December 31, 1991). Model prediction statistics were calculated using the results from both models to quantitatively evaluate the model performance. Scatterplots of observed vs. simulated values were prepared to visualize the predicted results from both models.

**Results and discussion**

The major output variables for this test were the surface runoff through the outlet of the Dry Lake site and the groundwater table depth, which was taken as the field average.
from all wells for the observations and as the mathematic average of predicted groundwater table depths form the four land segments for the model simulation.

Continuous simulation of surface runoff is shown in Figure 3-17 for both models against the observed data for the period from August 1989 through October 1991. Both ACRU2000 and FHANTM successfully captured major rainfall events in the calibration period but missed a few rainfall events during the verification period. There were some underestimations and overestimations of event hydrograph values by both models. Figure 3-18 illustrates the comparisons of cumulative surface runoff for the whole simulation period. It appears that both models’ predictions agree with each other fairly well throughout the simulation period. Furthermore they agree well with the observed cumulative runoff during the calibration period. However, they overestimated the observed data between the middle of January 1991 through July 1991, and underestimated the observed data throughout the rest of the simulation period. Similar to FHANTM, the modified ACRU2000 model performed better during the calibration period than it did during the verification period.

Figure 3-19 compares continuous simulations of groundwater table depth from the modified ACRU2000 model and FHANTM to the observed data for August 1989 to December 1991. A better agreement is observed during the calibration period for both models, while a slightly larger deviation from the observed water table depth data observed for both models in the verification period.

Considering different weather conditions for calibration and verification periods, it is apparent that the calibration of FHANTM was done in a relatively dry period whereas the verification was made in a relatively wet period. The difference in weather
conditions for both periods could cause the calibrated parameters by FHANTM to be suboptimal for the verification period. Since the same calibrated parameters were used in the modified ACRU2000 model, it is not surprising that similar results were obtained.

Statistics can be used to quantitatively address the difference in both models’ performance in simulating the observed conditions. As shown in Table 3-7, six statistics including bias, RE, RMSE, CV, $R^2$ and NS, introduced earlier in Chapter 2, were calculated. Statistics bias, RE, RMSE, and CV in runoff for the modified ACRU2000 model are slightly larger than those for FHANTM while $R^2$ and NS are a little smaller than those for FHANTM. And all statistics except NS in groundwater table are slightly larger than those for FHANTM. The comparisons of these statistics imply that FHANTM more accurately predicted in both runoff and water table depth than the modified ACRU2000 model. However, considering the modified ACRU2000 model was not calibrated specifically for the Dry Lake site, both model’s predictions are acceptable.

Furthermore, the Dry Lake Dairy #1 site is very small with an area of 5.9 ha and uniform parameters were used over the simulation domain. Therefore, the advantages of a distributed model like the modified ACRU2000 model may not be demonstrated by this example. It maybe possible that better results could be achieved by the ACRU2000 model if there were sufficient data to calibrate spatially distributed parameters directly for this model.

Scatterplots of observed versus predicted surface runoff and groundwater table depth were prepared to further visualize the overall performance of these models. Figure 3-20 shows the linear plot for surface runoff depth. FHANTM’s predictions fall closer to the 1:1 line than those from ACRU2000, while ACRU2000’s tend to underpredict surface
runoff more often than FHANTM. However, the linear plot for groundwater table depths (see Figure 3-21) shows both models match the 1:1 line very well. From this analysis, it appears that the modified ACRU2000 model’s ability to predict groundwater table is similar to FHANTM, but its ability to predict surface runoff is slightly poorer than FHANTM’s for the Dry Lake Dairy #1 site.

**Concluding Remarks**

In this Chapter, a hydrologic model capable of multi-directional spatial simulation of overland flow and lateral groundwater flow was developed based on the existing ACRU2000 hydrologic model by adding new hydrologic components and modifying existing components.

A simulation sequence analysis was conducted using two different hypothetical scenarios to analyze the influence of the simulation sequence on model predictions, and also to test the accuracy of the modified model in simulating hydrologic processes by comparing with well-known physically-based models MIKE SHE and MODFLOW. Results indicate that different simulation sequences do lead to slightly different simulation results, but the predictions with different sequences are consistent when compared with those from MIKE SHE and MODFLOW. It was concluded that transferring water storage from the source land segment and updating water storages in the adjacent land segments immediately produces the smoothest and most reasonable results. When there are multiple simulation sequences to choose from, the one following the expected flow directions based on topography is reasonable. In addition, by comparing to results from MIKE SHE and MODFLOW, the modified model has been shown to simulate hydrology reasonably well.
A test was conducted to validate the modified ACRU2000 model by comparing with the lumped FHANTM model in the Dry Lake Dairy #1 site, Kissimmee River Basin, FL. From the comparisons and statistical analyses, it was concluded that the modified ACRU2000 hydrologic model is capable of adequately simulating overland flow and groundwater table at the Dry Lake Dairy #1 site, but the modified ACRU2000 model is not better than FHANTM. However, the modified ACRU2000 model was not calibrated but utilized input parameters calibrated by FHANTM. Thus the advantages of a distributed model like the modified ACRU2000 may not be demonstrated by this application. It maybe possible that better results could be achieved for the modified ACRU2000 if there are sufficient data to calibrate spatially distributed parameters directly from this model.
Figure 3-17. Comparisons of the continuous simulations of runoff from the modified ACRU2000 and FHANTM against the observed data.

Figure 3-18. Comparisons of the cumulative simulated runoff from the modified ACRU2000 and FHANTM with the cumulative observed data.
Figure 3-19. Comparisons of the continuous simulation of groundwater table depths from the modified ACRU2000 and FHANTM against the observed data.

Table 3-6. Model input parameters for the Dry Lake Dairy #1 site.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil layer depth</td>
<td>m</td>
<td>0.10</td>
</tr>
<tr>
<td>Soil porosity</td>
<td>m/m</td>
<td>0.40</td>
</tr>
<tr>
<td>Wilting point</td>
<td>m/m</td>
<td>0.11</td>
</tr>
<tr>
<td>Field capacity</td>
<td>m/m</td>
<td>0.15</td>
</tr>
<tr>
<td>Vertical saturated</td>
<td>m/s</td>
<td>3.56</td>
</tr>
<tr>
<td>hydraulic conductivity</td>
<td></td>
<td>E-07</td>
</tr>
<tr>
<td>Lateral saturated</td>
<td>m/s</td>
<td>4.44</td>
</tr>
<tr>
<td>hydraulic conductivity</td>
<td></td>
<td>E-05</td>
</tr>
<tr>
<td>Manning’s coefficient</td>
<td>m^1/3/s</td>
<td>0.1</td>
</tr>
<tr>
<td>Brooks-Corey h</td>
<td>cm</td>
<td>40.0</td>
</tr>
<tr>
<td>Brooks-Corey λ</td>
<td></td>
<td>1.60</td>
</tr>
<tr>
<td>Brooks-Corey θ</td>
<td>m/m</td>
<td>0.11</td>
</tr>
<tr>
<td>Surface maximum</td>
<td></td>
<td>0.005</td>
</tr>
<tr>
<td>depressional storage</td>
<td>m</td>
<td>0.005</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td></td>
<td>0.4, 0.5, 0.6, 0.7, 0.85, 0.9, 0.85, 0.85, 0.6 for 12 months</td>
</tr>
</tbody>
</table>

*aCalibrated values by Tremwel (1992); bEstimated values.

Table 3-7. Statistics for the simulated surface runoff and groundwater table depths by the modified ACRU2000 and FHANTM.

<table>
<thead>
<tr>
<th>Statistics</th>
<th>bias</th>
<th>RE</th>
<th>RMSE</th>
<th>CV</th>
<th>R^2</th>
<th>NS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff</td>
<td>ACRU2000</td>
<td>-0.27</td>
<td>-0.37</td>
<td>0.74</td>
<td>1.03</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>FHANTM</td>
<td>-0.17</td>
<td>-0.24</td>
<td>0.61</td>
<td>0.86</td>
<td>0.56</td>
</tr>
<tr>
<td>Water Table</td>
<td>ACRU2000</td>
<td>12.73</td>
<td>-0.15</td>
<td>23.26</td>
<td>-0.27</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>FHANTM</td>
<td>9.79</td>
<td>0.00</td>
<td>22.23</td>
<td>-0.26</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Statistics were calculated using the predictions from both calibration and verification periods. Units of bias and RMSE for runoff and water table depth are cm. The rest of statistics are unitless for both variables.
Figure 3-20. Scatterplots of observed vs. simulated surface runoff depths predicted by the modified ACRU2000 and FHANTM.

Figure 3-21. Scatterplots of observed vs. simulated groundwater table depths predicted by the modified ACRU2000 and FHANTM.
CHAPTER 4
NUTRIENT SIMULATION MODEL

Introduction

Nutrient components were not included in the original ACRU (v3.00). After the model was entirely restructured into an object-oriented framework using the Java programming language (ACRU2000), Campbell et al. (2001) incorporated a nutrient module (ACRU-NP), which was patterned after transformation and transport concepts used in GLEAMS (Leonard et al., 1987; Knisel and Davis, 1999). The goals of Campbell’s work were to add capacities in ACRU2000 to 1) simulate nitrogen (N) and phosphorus (P) losses in surface runoff, sediment transport, and leaching, 2) simulate N and P cycling in the soil-water-plant-animal system, and 3) simulate N and P mass balances in the watershed system. Since GLEAMS includes most of these capacities in its current version it was used as a guide in development (Campbell et al., 2001). The module includes rainfall, irrigation, fertilizers, plants, and animal wastes as potential nutrient sources and represents management impacts on N and P transformation and transport (Campbell et al., 2001). Nutrient simulation requires a wide range of inputs including soil properties, irrigation parameters, crop parameters, nutrients in residues, fertilizer application and also tillage operations. A few adjustments were made to tailor the performance of GLEAMS when it was recoded into ACRU2000, including the significant modification to include the capacity to simulate grazing of pastures.

However, ACRU-NP module was incapable of simulating multidirectional lateral nutrient transport between land segments through either surface or subsurface water
movement. The lateral nutrient transport component in ACRU-NP was mainly designed for transporting nutrients dissolved in runoff and adsorbed in sediments through single outflow from one land segment. Considering the important mechanisms for delivering nutrients into downstream water bodies through both lateral surface and subsurface water movement in south Florida, it was necessary to modify the model to simulate lateral nutrient transport. Additionally, the original algorithm for dealing with the soil-surface nutrient exchange is a process of nutrient extraction and adsorption, with the ratio for partitioning the nutrients between the water and soil phases being a function of clay content. This method has the potential to overestimate the nutrients adsorbed onto soils but underestimate the nutrient released into surface water, especially for south Florida flatwood soils that contain low clay contents. To accurately simulate nutrient dynamics, it was necessary to modify this methodology. Moreover, the testing of the nutrient module within the framework of ACRU2000 has not been reported in the literature. Consequently, the major purpose of this work was to modify the existing ACRU-NP module to enable multidirectional spatial nutrient transport and test the modified model in simulating nutrient dynamics in south Florida flatwoods soils.

The major modifications presented in this chapter include adding new components to enable multi-directional spatial transport of N and P through surface runoff and lateral groundwater flow, and new conservative solute transport components to strengthen the capacities of the module to meet future needs. In addition, several existing nutrient transformation processes including ammonification, nitrification, P mineralization, immobilization, and denitrification were modified by Martinez (2006) and utilized in the model presented here.
Similar to the hydrologic processes, the modified nutrient components are grouped into vertical and lateral processes as shown in Appendix A. The vertical processes consist of N and P transport and transformation processes, and conservative solute transport, along the soil profile. These processes are executed after the vertical hydrologic processes. The lateral processes include the lateral N, P and conservative solute transport components, which are executed after the horizontal hydrologic processes. Appendix A lists the individual processes and the order that these processes are simulated in the context of the coupled modeling system. A daily time step is used in the nutrient module.

In the following sections, the nutrient components are briefly discussed. Details regarding the components taken from GLEAMS can be found in Knisel et al. (1993) and Fraisse and Campbell (1997). Processes developed in this work are discussed extensively. A conservative solute test (an extension of the hypothetical study in Chapter 3) is introduced to investigate the accuracy of the solute transport performance by comparing with the established particle tracking model PMPATH (Chiang and Kinzelbach, 2005). Following that, an application of the modified model to beef cattle pastures in the Buck Island Ranch, Lake Okeechobee Basin, FL is conducted, which includes model calibration, verification and sensitivity analysis. Conclusions regarding the model development and performance are summarized at the end of this chapter.

**Nutrient Components**

**Nitrogen Cycle Components**

A schematic representation of the N components in GLEAMS is shown in Figure 4-1. N in the soil is divided into six classifications including nitrate-N (NO₃-N), ammonium-N (NH₄-N), fresh organic N (crop residues and roots), organic N from animal
wastes, active soil N, and stable soil N. Each soil layer, as well as the soil surface, has its own set of these pools. Some of the compartments delineated in Figure 4-1 are for the ground surface only (grain, stover, atmospheric N, and assimilated N); some are for both surface and subsurface computational soil layers (fresh organic N in crop residue and roots, fertilizer, nitrate, ammonia, and organic N in animal waste); and the active and stable soil N occurs only in the subsurface. Sources of N include atmospheric N (rainfall), fertilizer N, biological N fixation, and the organic N pool (crop residue, roots and animal waste). Sinks for N are atmospheric N (denitrification and volatilization), plant uptake, runoff, erosion, and percolation. Nitrogen can be transformed by ammonification, nitrification, immobilization, denitrification, and volatilization.

Figure 4-1. Schematic representation of the GLEAMS nitrogen cycle (AM = ammonification; NI = nitrification; DN = denitrification; VL = volatilization; IM = immobilization; UP = uptake; FX = fixation) (Knisel et al., 1993).
Nitrogen including NO₃-N and NH₄-N may be transported with surface runoff and lateral groundwater flow from one land segment to its neighboring land segments. To calculate the amount of nitrogen mass moved with water flows, the concentrations of nutrients in the surface water and subsurface are calculated separately. These concentrations are then multiplied by the volume of water moving along each pathway to obtain the mass of nutrients lost through surface runoff and lateral groundwater flow from each land segment to its neighboring land segments, streams or water bodies.

**Mineralization**

N mineralization is considered a two-stage process in GLEAMS - ammonification followed by nitrification. In the soil, organic N is divided into two pools: a stable pool from which no mineralization occurs (C: N > 25), and an active pool available for mineralization (C: N < 25). The active pool can be replenished from flux between it and the stable pool (a function of relative pool sizes), from fresh organic N from decomposing roots, and from decomposition of organic N in applied animal waste.

Ammonification of decomposing roots, other crop residues, and animal wastes in the soil is considered a first-order process and is a function of C:N and C:P ratios of the residue, temperature, and soil moisture content. Of the total NH₄-N released by animal waste in the soil, 20% is allocated to the active soil N pool with 80% going to an NH₄-N pool. Crop residues and animal waste on the surface use a similar function to determine ammonification rate but liberated NH₄-N stays on the surface in a soluble NH₄-N pool until moved into the soil by the next rainfall or irrigation event. As the C: N ratio of the soil active N pool is set between 12:1 and 25:1, organic C is already partially accounted for and ammonification of the active N pool is a function of temperature and soil water.
content. Nitrogen flux from the active N pool can go to either the stable soil N pool or to the free NH₄-N pool.

The second stage of mineralization is nitrification, which converts N in the NH₄-N pool into NO₃-N. This is considered a zero-order process (not affected by the amount of NO₃-N or NH₄-N) and is modeled as a function of temperature and soil moisture. Nitrogen from the NH₄-N pool that is nitrified is transferred to the NO₃-N pool. Nitrification can also occur on the soil surface where it is a function of temperature and soil moisture. As with the soluble NH₄-N pool, the soluble nitrate pool on the soil surface remains on the soil surface until moved into the soil by rainfall. Once in the soil, these products join the appropriate pools in the soil.

**Immobilization**

Immobilization occurs when either NO₃-N or NH₄-N is used by soil microbes for growth. Once incorporated into the microbe, the N is unavailable for uptake by plants and remains so until the death and decomposition of the microbe. Thus, factors that affect the growth rate of microbes are important in driving immobilization. Immobilization of both soil and surface N is a function of the amount of NO₃-N and NH₄-N available, C:N ratio, and C:P ratio. Immobilization is limited to 95% of total available NO₃-N and NH₄-N. Immobilized N in the soil can end up either in the fresh organic N pool or in the stable soil N pool.

**Denitrification**

Denitrification is generally thought to require anaerobic conditions and available organic matter to proceed at an optimum pace. Denitrification of N from the soil NO₃-N pool to the atmosphere is driven by available organic carbon, soil moisture (an indicator of available oxygen), and temperature. Martinez (2006) modified the denitrification
process using a threshold water content to determine whether denitrification will occur in each layer. The threshold content was assumed to correspond to a saturation value of 0.8 as in the WAVE model (Vanclooster et al. 1996).

**Runoff, sediment transport and percolation**

Nitrogen lost from the top 1 cm active surface layer of soil is primarily a function of the amount of water moving (percolation or runoff) and a combination of nutrient and soil characteristics in ACRU-NP. The concentration of NH$_4$-N in the water is dependent on how much is adsorbed onto the soil, which is a function of the clay content of the soil. When runoff begins, the surface active layer interacts with the runoff stream, imparting some of the soil chemicals to the runoff. The amount of NH$_4$-N adsorbed to the top 1 cm of soil is also available for erosion where loss is a function of sediment loss and adsorbed NH$_4$-N concentration.

However, the original design was based on the assumption that no ponded water was left on the surface on a given day. Thus it may not be true in reality. To consider the nitrogen concentration in ponded surface water, Martinez (2006) developed a process which uses a mixing-type model to determine the exchange of nutrients between ponded water and the top-most soil layer. This process allows nutrients to move upward or downward depending on the concentration gradients between ponded water and soil water.

Loss of N to percolation is a function of concentration of NO$_3$-N and NH$_4$-N available for movement (again, functions of partitioning between soil and water phases) in each soil layer and the volume of water percolating through the soil.
Uptake, evaporation, and fixation

Nitrogen uptake was patterned after that in the EPIC model (Sharpley and Williams, 1990) for estimation of nitrogen demand in ACRU2000. All crops differ in their affinity for nitrate or ammonium, but it is assumed that nitrate and ammonium uptake is equal to the relative mass of each species in the soil layer from which transpiration occurs. Plant demand for N is a function of the concentration of N in the crop, the growth ratio of the plant (current accumulated LAI as a proportion of potential LAI at maturity) and potential yield of the crop. Potential uptake of N is a function of available NO₃-N and NH₄-N and the amount of plant transpiration (calculated in the hydrology component as a function of available water in the root zone). If supply is less than demand, an N stress factor that represents the N deficiency in soil (further discussion in Chapter 5), is calculated and used to lower potential growth.

In modeling N uptake by legumes N fixation occurs in this model only on days when concentration of NO₃-N + NH₄-N in soils is below a crop/soil-specific threshold value. When fixation occurs, the amount is set equal to demand. Nitrogen fixation may also be curtailed during early crop development.

Soil water can move upward in the soil profile in ACRU2000 as discussed in Chapter 2. NO₃-N and NH₄-N in the soil solution can move upward with the soil water to successive soil layers. The rate of upward movement of NO₃-N and NH₄-N is a function of the concentrations of NO₃-N and NH₄-N, respectively, in solution in the lower layer and upward flux amount. Soil NH₄-N is not lost to the atmosphere by volatilization in this model.
Rainfall and fertilizer

Ammonium and nitrate contained in rainfall are instantaneously available nitrogen. Their concentrations vary throughout the year but in the model it is assumed that all of the rainfall nitrogen is in the form of nitrate and the concentration in rainfall remains the same throughout the model simulation period (Fraisse and Campbell, 1997).

Since NO₃-N and NH₄-N pools are separately maintained, and nitrification and ammonification processes are simulated separately as well, nitrate and ammonia fertilizers are distinguished in application. Fertilizer and animal waste can be applied on soil surface, incorporated, injected, or applied as fertigation.

Ammonia volatilization

NH₄-N in the soil solution is not lost to volatilization. Volatilization losses from surface applied animal wastes, however, are assumed to occur. The extent of the losses is a function of the NH₄-N content applied in the waste and the air temperature. Losses are assumed to occur for a period of one week following application.

Surface and subsurface lateral nitrate nitrogen transport

To calculate the mass of nutrients carried by multi-directional spatial overland flow and lateral groundwater flow, the concentrations of nutrients are multiplied by the volume of water moving in each pathway to obtain the mass of nutrients lost through surface runoff and lateral groundwater flow to neighboring land segments, streams or water bodies. The concentrations of nitrate in surface runoff and lateral groundwater flow are calculated:

\[
CNO₃ₗ,ₗ,ₗ = \frac{SNO₃ₗ,ₗ,ₗ}{WMₗ,ₗ,ₗ} \quad (4-1)
\]

\[
CNO₃ₗ,ₗ,ₗ = \frac{SNO₃ₗ,ₗ,ₗ}{WMₗ,ₗ,ₗ} \quad (4-2)
\]
where the subscript s and d indicate the source and destination land segments, and i and j are the soil layers of source and destination land segments, respectively; CNO3Ws,d,i and CNO3Ws,i,j are the concentrations of nitrate in surface runoff and saturated soil layers \([M/L^3]\), respectively; SNO3s,d,i and SNO3s,i,j are the nitrate masses stored in surface runoff and saturated soil layers \([M/L^2]\); WM,s,d,i is the water storage on the ground surface \([L]\) and WM,s,i,j is the water storage in the saturated soil layers \([L]\) before overland flows and lateral groundwater flows are transferred to the neighboring land segments.

\[
WM_{s,d,i} = WS_s + \sum Q_{s,d,i} \quad (4-3)
\]

\[
WM_{s,i,j} = WS_{s,j} + \sum Q_{s,i,j} \quad (4-4)
\]

where WS_s is the current water storage \([L]\) and Q_{s,d,i} is the transferred overland flow from the source land segment to its neighboring land segments \([L]\); WS_{s,j} is the current water storage in the jth saturated soil layer of the source land segment \([L]\); Q_{s,i,j} is the transferred lateral groundwater flow from the jth layer to its counterpart soil layer within the soil of the ith neighboring land segment \([L]\).

Nitrate transported through surface runoff and lateral groundwater flow is calculated:

\[
RONO_3_{s,d,i} = CNO3Ws,d,i \times Q_{s,d,i} \quad (4-5)
\]

\[
RONO_3_{s,i,j} = CNO3Ws,i,j \times Q_{s,i,j} \quad (4-6)
\]

where RONO3_{s,d,i} is the nitrate mass removed from source to destination land segments or water bodies through surface runoff \([M/L^2]\); RONO3_{s,i,j} is the nitrate removed from layer j in the source land segment to layer j in the destination land segment through the lateral groundwater flow \([M/L^2]\).
The conservation of nitrate mass is checked for both nitrate mass transported through surface runoff and lateral groundwater flows. The method for checking the mass balance can be expressed as:

\[
\begin{align*}
\text{TNM} &= \text{ANM} \quad \text{TNM} \geq \text{ANM} \\
\text{TNM} &= \text{TNM} \quad \text{TNM} < \text{ANM}
\end{align*}
\] (4-7)

where TNM is the nutrient mass to be transferred \([\text{M}/\text{L}^2]\) and ANM is the available mass in storage \([\text{M}/\text{L}^2]\) on ground surface or soil layers. This approach is applied to the following ammonium and labile P as well.

**Surface and subsurface lateral ammonium nitrogen transport**

The concentrations of ammonium in runoff and lateral groundwater flow are calculated:

\[
\text{CNH4W}_{s,d,i} = \frac{\text{AMON}_{s,d,i}}{\text{WM}_{s,d,i}}
\] (4-8)

\[
\text{CNH4W}_{s,i,j} = \frac{\text{AMON}_{s,i,j}}{(\text{CNHKD}_{s,i,j} \times \text{SOILMS}_{s,i,j}) + \text{WM}_{s,i,j}}
\] (4-9)

where \(\text{CNH4W}_{s,d,i}\) and \(\text{CNH4W}_{s,i,j}\) represent the concentrations of ammonium in the surface runoff and saturated soil layers \([\text{M}/\text{L}^3]\); \(\text{AMON}_{s,d,i}\) and \(\text{AMON}_{s,i,j}\) are the ammonium in surface runoff and the saturated soil layer \(j\) \([\text{M}/\text{L}^2]\); \(\text{CNHKD}_{s,i,j}\) is the ammonium partitioning coefficient for each saturated soil layer \([\text{L}^3/\text{M}]\); \(\text{SOILMS}_{s,i,j}\) is the soil mass of each saturated soil layer \([\text{M}/\text{L}^2]\).

The ammonium partitioning coefficient, \(\text{CNHKD}_{s,i,j}\), is estimated using an empirical relation to account for the range of clay content \(\text{CL}_{s,i,j} \,[\%]\) as

\[
\text{CNHKD}_{s,i,j} = 1.34 + 0.083 \times \text{CL}_{s,i,j}
\] (4-10)

The soil mass in each soil layer, \(\text{SOILMS}_{s,i,j}\), is obtained by multiplying the bulk density, \(\text{SOILBD}_{i,j}\), of the soil layer \([\text{M}/\text{L}^3]\), and \(\text{DEPTH}_{i,j}\), the depth of the soil layer \([\text{L}]\):
\[ \text{SOILMS}_{s,i,j} = \text{SOILBD}_{s,i,j} \times \text{DEPTH}_{i,j} \] (4-11)

Ammonium removed through surface runoff and lateral groundwater flow is calculated:

\[ \text{RONH}_4_{s,d,i} = \text{CNH}_4W_{s,d,i} \times Q_{s,d,i} \] (4-12)

\[ \text{RONH}_4_{s,i,j} = \text{CNH}_4W_{s,i,j} \times Q_{s,i,j} \] (4-13)

where \( \text{RONH}_4_{s,d,i} \) and \( \text{RONH}_4_{s,i,j} \) are the ammonium removed through surface runoff and layer lateral flow \([\text{M/L}^2]\).

**Phosphorus Cycle Components**

![Phosphorus Cycle Components Diagram](image)

Figure 4-2. Schematic representation of the GLEAMS phosphorus cycle (MN = mineralization; IM = immobilization; UP = uptake) (Knisel et al., 1993).

Phosphorus is divided into six components (Figure 4-2). Many are analogous to the N classifications including labile-P, organic humus, fresh organic P (crop residues and roots), organic P from animal wastes, active inorganic P, and stable inorganic P. Each soil layer as well as the soil surface has its own set of these pools. Sources of P include atmospheric P (rainfall), fertilizer P, inorganic P, and the organic P pool. Sinks
for P are plant uptake, runoff, erosion (SED on figure), and percolation. Phosphorus can
be transformed by mineralization and immobilization.

Labile P may be transported with surface runoff and lateral groundwater flow from one land segment to its neighboring land segments. To calculate the amount of nutrient mass moved with water flows, the concentrations of nutrients in the water are calculated. These concentrations are then multiplied by the volume of water moving in each pathway to obtain the mass of nutrients lost through surface runoff and lateral groundwater flow from this land segment to neighboring land segments, streams or water bodies.

**Mineralization**

P mineralization is considered a single step first-order process (Jones et al., 1984). Mineralization of the organic humus pool supplies the labile P pool. Mineralization of organic humus is a function of soil moisture, temperature, and P content, and uses the same temperature and moisture factors as were used in the N component. The ratio of the size of the active soil N pool to the stable soil N pool is also used to partition the soil organic humus pool into the mineralizable fraction.

Mineralization of fresh organic P (roots and crop residue in the soil) supplies the soil humus pool. The rate of mineralization is a function of residue composition, C:N and C:P ratios, temperature and soil moisture. The same function is used to calculate P mineralization from residue on the soil surface as well. As in the EPIC model (Sharpley and Williams, 1990), 75% of mineralized P is added to the labile P pool and 25% to the organic humus pool.

Mineralization of P in animal wastes is a function of temperature and soil moisture as well as a rate constant. In accordance with Bhat et al. (1981), 75% of mineralized P is allocated directly to the labile P pool and 25% to the organic humus pool.
A further similarity to the N component is the flux between the active inorganic P pool and the stable pool. This flux is a function of the size of the active and labile P pools as well as temperature, soil moisture and calcium carbonate concentration of the soil (which affects sorption). It is assumed that at equilibrium, the stable pool mass will be four times the active pool mass (Sharpley and Williams, 1990). Mineralized P from the active pool can also be allocated to the labile P pool.

**Immobilization**

The same decomposition rate used in calculating immobilization of N is used in calculating immobilization of P. The decomposition rate is a function of temperature, soil moisture and the C:N and C:P ratios of the residue. Immobilization rate is also a function of the concentration of labile P in the soil layer. It is assumed that residue is 40% C and that the microbes assimilate 40% of the C. As with N immobilization, P immobilization is also limited to 95% of labile P. The same factor is used for both nutrients so a shortage of N can limit P immobilization and vice versa. Immobilization of surface P is calculated in the same way.

**Runoff, sediment, percolation**

As with N, the amount of P lost in runoff and percolation depends on the partitioning of P between the soil and water phases. In GLEAMS, the amount of P adsorbed to the soil is a function of the clay content of the soil. This method, however, greatly overestimates the partitioning coefficient for the high water table flatwoods Spodosol soils and underestimates the P concentration in soil water. An alternative method (by Portier KM according to Fraisse and Campbell (1997)) obtained through a study in Lake Okeechobee watershed determined the partitioning coefficient as a function of the content of magnesium, organic carbon and/or aluminum. Martinez (2006)
introduced a mixing-type model to calculate P transport between the ponded water and soil water, similar to that for N.

As with the N component, the actual amount of P lost in runoff or percolation is a function of soluble P available and the water flux. Losses to erosion are calculated the same as for N with corresponding losses from the animal waste, active mineral P and stable mineral P pools as well as additional P lost from the humus pool.

**Uptake and evaporation**

Potential P uptake is calculated independently of demand, as a function of transpiration and concentration of labile P in the soil water. Plant P demand is the function of the concentration of P in the crop, the growth ratio of the plant and the potential yield of the crop. If supply is less than demand, uptake is equal to the supply. Otherwise, uptake is equal to the demand. Unlike the nitrogen component, growth is assumed not to be limited by P deficiency in the original ACRU2000. However, it may not be true in reality. A P stress factor was introduced through this work to represent the P stress on plant growth due to P deficiency (detailed discussion in Chapter 5).

P moves upwards in the soil profile with upward soil water flux. The amount lost to the next higher layer is a function of the concentration of labile P in the soil water in the current soil layer and the volume of upward flux. However, it is assumed that there are no volatilization losses of P.

**Rainfall and fertilizer**

The GLEAMS model includes an option to input the rainfall N concentration but it does not allow input of rainfall P levels. This function was added to ACRU-NP by Campbell et al. (2001) and P in rainfall and irrigation water is accounted for in the same way as for N.
Both rainfall P and fertilizer P are assumed to be soluble and available to the plant as soon as they are applied. If the fertilizer is surface applied and not incorporated, it is stored on the surface and moved to the surface layer soluble (labile) pool on the first occurrence of rain or irrigation following the application. All P from incorporated fertilizers and infiltrated rainfall is added immediately to the labile P pool. Availability of P from organic wastes is more gradual and was discussed in the mineralization and immobilization sections.

**Surface and subsurface lateral labile phosphorus transport**

The concentrations of labile P in runoff and lateral flow are calculated:

\[
CPLABW_{s,d,i} = \frac{PLAB_{s,d,i}}{WM_{s,d,i}} \quad (4-14)
\]

\[
CPLABW_{s,i,j} = \frac{PLAB_{s,i,j}}{(CPKD_{s,i,j} \times SOILMS_{s,i,j} + WM_{s,i,j})} \quad (4-15)
\]

where CPLABW_{s,d,i} and CPLABW_{s,i,j} represent the concentrations of labile P in the surface runoff and in the saturated soil layers, respectively [M/L³]; PLAB_{s,d,i} and PLAB_{s,i,j} are the labile P in surface runoff [M/L²] and in the saturated soil layer j [M/L²]; CPKD_{s,i,j} is the labile P partitioning coefficient in the saturated soil layer [L/M].

In GLEAMS, it was assumed that P is partially adsorbed to the soil clay fraction. However, this assumption is not adequate for sandy, high-water-table flatwoods spodosol soils. Therefore, an algorithm was developed by Portier (personal communication, referenced in Fraisse and Campbell (1997)) to represent the P partitioning coefficient, CPKD_{s,i,j}, as a function of the content of double-acid-extractable magnesium (DAMGRD [mg/kg]), organic carbon (OCBRD [mg/kg]) and/or oxalate-extractable aluminum (OXALRD [mg/kg]) in each soil horizon:

For the A horizon
\[
CPKD_{s,i,j} = e^{2.2390} \quad \text{For \ DAMGRD} \geq 103.2 \quad (4-16)
\]

\[
CPKD_{s,i,j} = e^{-2.2233} \quad \text{For \ DAMGRD} < 103.2 \ \text{when \ OCBRD} \geq 1.865 \quad (4-17)
\]

\[
CPKD_{s,i,j} = e^{1.4420} \quad \text{For \ DAMGRD} < 103.2 \ \text{when \ OCBRD} < 1.865 \quad (4-18)
\]

For the E horizon

\[
CPKD_{s,i,j} = e^{4.2410} \quad \text{For \ OXALRD} \geq 496.45 \quad (4-19)
\]

\[
CPKD_{s,i,j} = e^{1.0480} \quad \text{For \ OXALRD} < 30.1 \quad (4-20)
\]

\[
CPKD_{s,i,j} = e^{1.4440} \quad \text{For} \ 30.1 \leq \text{OXALRD} < 496.45 \ \text{when} \ \text{DAMGRD} \geq 4.95 \quad (4-21)
\]

\[
CPKD_{s,i,j} = e^{1.7670} \quad \text{For} \ 30.1 \leq \text{OXALRD} < 496.45 \ \text{when} \ \text{DAMGRD} < 4.95
\]

\[
\quad \text{with} \ \text{OXALRD} < 57.25 \quad (4-22)
\]

\[
CPKD_{s,i,j} = e^{3.3500} \quad \text{For} \ 30.1 \leq \text{OXALRD} < 496.45 \ \text{when} \ \text{DAMGRD} < 4.95
\]

\[
\quad \text{with} \ \text{OXALRD} \geq 57.25 \quad (4-23)
\]

For the Bh horizon

\[
CPKD_{s,i,j} = e^{3.7510} \quad \text{For} \ \text{OXALRD} \geq 1327.5 \quad (4-24)
\]

\[
CPKD_{s,i,j} = e^{2.1950} \quad \text{For} \ \text{OXALRD} < 1327.5 \quad (4-25)
\]

For the Bw horizon

\[
CPKD_{s,i,j} = e^{3.2120} \quad \text{For} \ \text{OXALRD} \geq 570.8 \quad (4-26)
\]

\[
CPKD_{s,i,j} = e^{1.6040} \quad \text{For} \ \text{OXALRD} < 570.8 \quad (4-27)
\]

The soil mass for each soil layer, SOILMS_{s,i,j} is calculated using Equation (4-11).

Labile P removed through surface runoff and lateral groundwater flow is calculated:
\[ \text{ROLP}_{s,d,i} = \text{CPLABW}_{s,d,i} \times Q_{s,d,i} \quad (4-28) \]

\[ \text{ROLP}_{s,i,j} = \text{CPLABW}_{s,i,j} \times Q_{s,i,j} \quad (4-29) \]

where \( \text{ROLP}_{s,d,i} \) and \( \text{ROLP}_{s,i,j} \) are the labile P removed through surface runoff \([\text{M/L}^2]\) and layer lateral flow \([\text{M/L}^2]\).

**Conservative Solute Transport Components**

A transport module capable of simulating conservative tracers such as bromide and rhodamine WT (RWT) was added into the nutrient module through this work assuming only vertical and horizontal transport processes occur (i.e. no transformation processes). The vertical and horizontal transport processes were simulated as discussed for nitrate.

Martinez (2006) created several vertical processes to simulate the conservative solute transport through evaporation, soil water redistribution, and exchange between water in the top soil layer and ponded water. The evaporation solute transport process calculates the upward movement of a conservative solute in the soil due to evaporation, however solute is not allowed to move upward out of the soil surface layer by evaporation. The subsurface solute transport calculates the leaching of a conservative solute downward through the soil profile. A mixing-type model is used to determine the exchange of solute between ponded water and soil water in the top-most soil layer, driven by the solute concentration gradients. Surface and subsurface lateral transport processes added through this work are described below.

The concentrations of conservative solute in the ponded water on the ground surface and in the saturated groundwater are calculated:

\[ \text{CCONSOLW}_{s,d,i} = \text{CONSOL}_{s,d,i} / \text{WM}_{s,d,i} \quad (4-30) \]
where $C_{\text{CONSOL}W_{s,i,j}}$ and $C_{\text{CONSOL}W_{s,i,j}}$ are the concentrations of conservative solute in the ponded water and saturated soil layers [M/L³], respectively; $\text{CONSOL}_{s,d,i}$ and $\text{CONSOL}_{s,i,j}$ are the conservative solute mass on the ground surface and saturated soil layers [M/L²], respectively; $W_{M_{s,d,i}}$ is the water storage on the ground surface [L] and $W_{M_{s,i,j}}$ is the water storage in the saturated soil layers [L] as defined in Equations (4-3) and (4-4), respectively.

Conservative solute removed in surface runoff is calculated:

$$RO_{\text{CONSOL}_{s,d,i}} = C_{\text{CONSOL}W_{s,d,i}} \times Q_{s,d,i}$$  \hspace{1cm} \text{(4-32)}

where $RO_{\text{CONSOL}_{s,d,i}}$ is the conservative solute removed in surface runoff [M/L²]; $Q_{s,d,i}$ is the surface runoff generated on a given day from the current land segment to the $i$th neighboring land segment [L].

Conservative solute removed in lateral groundwater flow is calculated:

$$RO_{\text{CONSOL}_{s,i,j}} = C_{\text{CONSOL}W_{s,i,j}} \times Q_{s,i,j}$$  \hspace{1cm} \text{(4-33)}

where $RO_{\text{CONSOL}_{s,i,j}}$ represents the conservative solute removed in lateral groundwater flow from the layer $j$ to the $i$th neighboring land segment [M/L²]; $Q_{s,i,j}$ is the lateral flow in layer $j$ to the $i$th neighboring land segment [L].

Mass balance is checked for the conservative solute in both surface runoff and lateral groundwater flow as was described for N and P.

**Initial and Boundary Conditions**

Running the model requires good estimates for initial nutrient pools. This is especially true for validation comparisons with observed data. Because of the dynamics of the nitrate and ammonium processes, inaccurate initialization may not adversely affect
long-term simulation results. Initial values of different nutrient pools are very site
specific and are generally management dependent (Fraisse and Campbell, 1997). This is
especially true for systems with animal waste application and management activities such
as stocking, fertilization, and tillage operations. Model users should make every effort to
obtain good estimates of initial conditions, which may involve soil sampling and
analyses. However, soil samples commonly only determine certain nutrient variables
such as organic matter, total nitrogen, total phosphorus, nitrate, ammonium and available
phosphorus at a certain depth of soil. Stable, active mineral N and P and initial nutrient
pools in the deeper soil layers are usually unavailable. For a spatially distributed model,
the spatial distribution of initial nutrient pools is also required, which further increases
the level of effort. If initial values of the nutrient pools are not available, the model is set
up to use default values.

Agricultural activities such as stocking, fertilization, burning, etc. are treated as
time series inputs in the modified model. Nutrients from rainfall and irrigation (nitrate
and labile P only) and animal wastes must be specified as time series input and are added
to the appropriate nutrient pools.

**Model Testing and Validation**

**Conservative Solute Test**

To test the accuracy of the algorithm for the conservative solute transport
components added to ACRU2000, model results for a hypothetical scenario were
compared with those from PMPATH (Chiang and Kinzelbach, 2005), which is an
advective transport model using groundwater pore velocities from MODFLOW
(McDonald and Harbaugh, 1998).
Scenario description

The axisymmetric hypothetical domain with initial water levels below the ground surface used for testing groundwater movement (Case 2) in Chapter 3 was extended for this test. The hydrologic inputs remained the same as for the tests discussed in Chapter 3. In order to run the model together with the added conservative solute components, an initial solute mass has to be specified.

For the modified ACRU2000, it is assumed that 3kg of solute was initially present in the 3rd soil layer of each of central four land segments, and that this solute mass was uniformly distributed inside of that soil layer. However, PMPATH requires that an initial number of particles, rather than an initial solute mass, be specified for each element (equivalent to a soil layer in ACRU2000), with a maximum of 5000 particles per element. Furthermore, it is difficult to set up the initial particle distribution pattern inside an element so that it is completely uniform. After a few experiments, 4704 particles were placed as uniformly as possible in each 3rd soil layer element for each central land segment in PMPATH to represent the equivalent quantity of 3kg of solute. Thus, each particle is mathematically equivalent to a mass of 3kg/4704, and it is possible to convert the integer number of particles which appear inside a certain element into a mass of solute in PMPATH. For comparison with the simulated results from the modified ACRU2000, the PMPATH simulation was run using a daily time step for two years.

Results and discussion

Considering the axisymmetric distribution of solute mass, the simulated solute mass in the third and fourth soil layers of LS20, LS21 and LS26 from the modified ACRU2000 model were selected to compare with the results obtained from PMPATH (see Figure 4-3). This figure shows that there is a good agreement, particularly during
the first year, between the models for the predicted solute mass in layer 3 for LS21, which is one of the central land segments that received an initial dose of 3kg solute in this layer. During the second year a larger discrepancy is observed in layer 3 of LS21. However, a good agreement was found in the predicted solute mass for the 4th soil layer throughout the two-year simulation. Smaller bias and RMSE values were found for layer 4 than for layer 3 in LS21 (see Table 4-1). Similar to LS21, results for LS20 seem to be better for layer 4 than for layer 3. However, during the second year more solute mass is predicted in layer 3 by ACRU2000 than by PMPATH. A poorer agreement is observed in both layers 3 and 4 for LS26, which is a land segment receiving water flow and solute transport through LS20 instead of from LS21 directly. The predicted solute mass from ACRU2000 is obviously larger than that predicted by PMPATH for both layers. Large negative values of RE and NS in Table 4-1 indicate the agreement between the two models is not as strong in LS26 as it appears for LS21 and LS20.

<table>
<thead>
<tr>
<th>Statistics*</th>
<th>Bias (kg)</th>
<th>RE (-)</th>
<th>RMSE (kg)</th>
<th>CV (-)</th>
<th>$R^2$ (-)</th>
<th>NS (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS21</td>
<td>Layer 3</td>
<td>0.1947</td>
<td>0.0833</td>
<td>0.2582</td>
<td>0.1104</td>
<td>0.8652</td>
</tr>
<tr>
<td></td>
<td>Layer 4</td>
<td>-0.0297</td>
<td>-0.1095</td>
<td>0.0872</td>
<td>0.3217</td>
<td>0.6491</td>
</tr>
<tr>
<td></td>
<td>Layer 3</td>
<td>-0.0727</td>
<td>-0.4216</td>
<td>0.1093</td>
<td>0.6336</td>
<td>0.7324</td>
</tr>
<tr>
<td></td>
<td>Layer 4</td>
<td>-0.0049</td>
<td>-0.3392</td>
<td>0.0088</td>
<td>0.6101</td>
<td>0.7497</td>
</tr>
<tr>
<td></td>
<td>Layer 3</td>
<td>-0.0130</td>
<td>-0.9029</td>
<td>0.0173</td>
<td>1.2011</td>
<td>0.7303</td>
</tr>
<tr>
<td></td>
<td>Layer 4</td>
<td>-0.0014</td>
<td>-0.8536</td>
<td>0.0018</td>
<td>1.1340</td>
<td>0.6080</td>
</tr>
</tbody>
</table>

*Statistics were calculated using the predictions from PMPATH as the observed values.

After carefully examining the outputs for each land segment in the domain, it was found that at the end of the two-year simulation period PMPATH did not transport solute mass to the land segments located along the domain boundary, while in ACRU2000 some solute mass were predicted to reach the boundary cells in both layers 3 and 4. This finding indicates that the solute movement is slightly slower in PMPATH than it is in the
ACRU2000 model. In ACRU2000, groundwater flow always carries a certain amount of solute due to the assumption of uniform distribution of solute within the land segment layer. However, in the PMPATH the particle tracking algorithm does not transport particles from one element to the next until it travels the distance from where it is originally located to the face between the two elements. Although the water movement was a little faster in MODFLOW than in ACRU2000, the concentrations predicted in each element of the PMPATH model are smaller than predicted by ACRU2000. However, in spite of the difference in assumptions made by these models, the results illustrated in Figure 4-3 indicate that they produce qualitatively similar results.
Figure 4-3. Comparisons of the solute mass in the 3rd and 4th soil layers of selected land segments between the modified ACRU2000 and PMPATH (note change in scale).
Application at Buck Island Ranch, Lake Okeechobee Basin, Florida

Project description

To evaluate the ability of the modified ACRU2000 model to predict non-point source nutrient pollution, especially P loading, from beef cattle ranches in the Lake Okeechobee region, the model was applied to several isolated pastures at the Buck Island Ranch in the Lake Okeechobee Basin.

Figure 4-4. Location of MacArthur Agro-ecology Research Center (MAERC, 2004).

The experimental site at the MacArthur Agro-ecology Research Center (MAERC) at Buck Island Ranch, Highlands County, Florida (see Figure 4-4) consists of 16 pastures, eight 16.72-ha improved summer pastures with stocking from May to October and eight 26.76-ha semi-improved winter pastures with stocking from November to April. Four stocking rate treatments, including 0, 15, 20 and 35 cow-calf pairs per pasture that represent non-grazing, low, medium, and high-grazing, respectively, were implemented
for this experiment. Each of the stocking densities had two replicates in each of 16 winter and summer pastures. Figure 4-5 shows the layout of pastures and the instrument locations. Each of the pastures was individually fenced and ditched to capture surface runoff through a single trapezoidal flume. Nutrient concentrations, including total phosphorus (TP), soluble-reactive phosphorus (SRP), total N (TKN), nitrate + nitrite (NO₃⁻) and ammonium (NH₄⁺) were measured from water samples collected using ISCO automatic samples installed in each flume. Data collection started on May 19, 1998 for the summer pastures and on May 21, 1998 for the winter pastures, and continued through December 2003, interrupted only by occasional equipment malfunctions (MAERC, 2004). The winter pastures have two meteorological stations and the summer pastures have one station. These meteorological stations were installed on May 21, 1998 to record rainfall, windspeed and direction, air temperature, relative humidity, and solar radiation using Campbell Scientific CR10X dataloggers. In addition, there were 5 tipping bucket rain gages installed throughout the pastures to record rainfall. A main weather station is located at the Ranch headquarters, which operated throughout the experiment, where manual rainfall readings are taken daily and a datalogger records air temperature, relative humidity, windspeed and direction at 3.0 m and 9.1 m, solar radiation, and soil temperature.

For the purpose of model application, four pasture sites, including W6, W7, S1 and S4, were selected for use. Considering the similarity in soil characteristics, and the limited measurements of water table and nutrient loads throughout the 6-year simulation period from each site, one site each from the summer and winter pastures was used for calibration and the other one for verification. This allows calibration over more varied
weather conditions with more observations at one site than if both calibration and verification were performed at each site. W6 and S4 were used for model calibration and W7 and S1 for verification.

Figure 4-5. General layout of the project field (S1-S8 indicates eight 16.72-ha summer pastures and W1-W8 represent eight 26.76-ha winter pastures) (MAERC, 2004).

Tables 4-2, 4-3, and 4-4 list the management practices applied at the four selected pasture sites. Table 4-2 shows that the two calibration sites W6 and S4 had a stocking rate of 15 cow-calf pairs and the two verification sites W7 and S1 had no stocking throughout the simulation period. Manure application rates were initially set at 0.0176 tons/ha and 0.0277 tons/ha of beef solid manure for W6 and S4, respectively, for each day when cattle were in the pastures. These rates were based on an estimated bodyweight for the Braford cattle of 1,200-lbs and a daily excretion of 63 lbs of manure (as excreted) /1,000-lb animal unit (USDA, SCS, 1996). Built-in values for the composition of manure code 8-beef slurry were used in the model to calculate daily N and P applications.
Ammonium nitrate fertilizer was applied on summer pastures S1 and S4 three times during the simulation period for a total of 56 kg/ha nitrogen on each application (see Table 4-3). Prescribed burns and accidental fires occurred in all four pastures at different times (see Table 4-4). In the model, when burns or fires occur, 95% of the biomass of the surface residue is removed.

The areas of the four selected pasture sites and the percentages of soil series within each pasture are listed in Table 4-5. Although multiple soil series exist in each selected pasture site, for this study it is assumed that W6 and W7 had the same soil characteristics, and S4 and S1 also had the same soil characteristics because both winter and summer pasture pairs have the same dominant soil types (see Table 4-5). Pineda fine sand was assumed as the base soil series for W6 and W7 and Felda fine sand was assumed for S4 and S1. In the model, W6 and W7 were each divided into 18 land segments with surface areas ranging from 0.6 ha to 2.6 ha. S4 and S1 were each divided into 12 land segments with surface areas ranging from 1.6 ha to 1.8 ha. This spatial discretization was determined based on the available topographic maps that show the contours of surface elevation and wetlands. Using this information, an elevation value was assigned to each land segment.

Setting up the initial input data and parameters is critical to guarantee the accuracy of model performance. However, due to the unavailability of spatially distributed data in these pasture sites, all initial physical and biochemical data were assumed to be the same for each land segment in the same pasture site except a few parameters including surface elevation, land segment area, initial water table depth, and boundary conditions (i.e. boundary width and hydraulic structure information). Model input parameters are
summarized in Table 4-6 for winter pastures W6 and W7 and Table 4-7 for summer pastures S4 and S1.

Initializing the nutrient pool parameters (see Tables 4-6 and 4-7) was difficult because there was little nutrient information available for soils and surface residues in any of these pastures. The literature data obtained from laboratory analyses of soil samples do not give a breakdown of all the nutrient pools in all soil layers of interest, and these soil analyses are typically limited to the plow layer since that may be the depth of most concern to researchers. Therefore, the procedure for setting up initial nutrient pools introduced in the FHANTM manual (Fraisse and Campbell, 1997) was adopted.

For each soil layer, nitrogen including all forms of nitrogen, i.e. mineralizable, stable organic, fresh organic, humus, ammonia, etc. was required model inputs. The total nitrogen (TN) was estimated for each computational soil layer using the data in Table 1 (Fraisse and Campbell, 1997). Nitrate-nitrogen (NO$_3$-N) was estimated using a concentration of 10 µg/g of soil in all soil layers. Ammonium nitrogen (NH$_4$-N) was estimated using a concentration of 2 µg/g of soil. Root residue from previous biomass productivity was estimated at the beginning of the simulation as 40 kg/ha and distributed vertically in the root zone. Stable mineral nitrogen was initialized by taking the difference between the TN and the rest of nitrogen pools except nitrate-N.

Phosphorus pools in the soil that must be initialized include fresh organic P in crop residue, organic humus P, labile P, and active and stable mineral P. According to Fraisse and Campbell (1997) soil organic humus can be estimated using the following relationships:

$$\text{SORGP} = 9.24 + 147.35 \times \text{TN}$$

For the plow layer

(4-9)
\[ \text{SORGP} = 11.25 + 148.58 \times \text{TN} \]  
For other horizons \hspace{1cm} (4-10)

where SORGP is soil organic humus [\(\mu g/g\)], and TN is total nitrogen [%]. The labile P was estimated to be 8.7% of SORGP for slightly weathered soils (Fraisse and Campbell, 1997). The active mineral P pool was estimated using the following relationship derived from Equation (12) (Fraisse and Campbell, 1997):

\[ \text{PMINP} = \text{PLAB}(1 - \text{PSP}) / \text{PSP} \]  
(4-11)

where PMINP is the active mineral P [kg/ha] and PSP is the P sorption coefficient that can be estimated according to Sharpley and Williams (1990)

\[ \text{PSP} = 0.0054 \text{BAST} + 0.116 \text{PH} - 0.73 \]  
(4-12)

where BAST is base saturation [%] and PH is the soil pH for slightly weathered soils.

The stable mineral P was set as four times active mineral P (Fraisse and Campbell, 1997). The fresh organic P is estimated as 10 kg/ha and distributed in the root zone (Fraisse and Campbell, 1997).

Using the above discussed relationships, the initial nutrient pools were set up for both N and P. Tables 4-6 and 4-7 list the calibrated N and P parameters based on the initial nutrient values. Although multiple vegetation species exist in each of selected sites, only one species, bahiagrass (*Paspalum notatum* Flügge) was assumed to exist for simplicity.

Model calibration was based on personal judgment and statistical analyses for four major output variables, i.e., groundwater table depth, runoff depth, and N and P loads. Calibration was performed for these output variables sequentially in the order listed above. During calibration, hydrologic parameters, including porosity, wilting point, saturated hydraulic conductivity, restrictive layer hydraulic conductivity, Manning’s
roughness coefficient, surface maximum depressional storage, and crop coefficient; and nutrient parameters, including rainfall P and N concentrations, active P, stable P, humus P, active N, and stable N, were varied within their physically reasonable ranges until the output variables were judged to be acceptable. It should be noted that the soil porosity and wilting point values for both W6 and S4 (see Tables 4-6 and 4-7) are smaller than typical values in flatwoods soils. These data were determined through the model calibration process. Due to lack of actual soil information and other data (such as crop coefficient), these calibrated parameters could be biased to a certain point. They can be improved when sufficient soil data become available in the future. Upon completion of model calibration, the resulting data sets were used for independent verification simulations. Statistical and visualization tools introduced in Chapter 2 were used to evaluate the model calibration and verification performance. Furthermore, the calculated statistics were compared with those from FHANTM by Sims (2004) for winter pastures. No comparison was made for summer pastures since no previous modeling has been performed on any of the summer pastures.

**Sensitivity analysis**

Sensitivity analyses were conducted by changing a given input parameter by a predetermined amount, with the other inputs held at their calibrated values, and running a simulation for the period of January 1, 1998 through December 31, 2003. The sensitivity analyses were made for the calibration sites W6 and S4. Hydrologic inputs (see Tables 4-8 and 4-10) selected for sensitivity analysis include soil porosity, wilting point, saturated hydraulic conductivity, restrictive layer hydraulic conductivity, Manning’s roughness coefficient, surface maximum depressional storage, and crop coefficient, and nutrient inputs (see Tables 4-9 and 4-11) selected for sensitivity analysis include rainfall P and N.
concentrations, active P, stable P, organic humus P, active N, stable N, and stocking and fertilizer rates. These choices were made as a result of the calibration process, reference material, and intuition gained during the process of developing this model. The sensitivity analyses were focused on two major hydrologic outputs including the total surface runoff from the site and maximum water table depth at the measurement location, and two major nutrient outputs including the total P and N loads from the site throughout the simulation period. Only the selected hydrologic input parameters were tested for the hydrologic outputs and all selected parameters were tested for the nutrient outputs.

For each input parameter, simulations were conducted for the base (calibrated) value(s) and increments of +50%, +10%, -10%, and -50%, one at a time. If a selected parameter could have different values by soil layer, then this parameter value was increased or decreased by a given percentage simultaneously for all soil layers. Tables 4-8 to 4-11 list the ranges of values for the selected hydrologic and nutrient parameters used in the sensitivity analyses for both calibration sites W6 and S4. Tables 4-12 to 4-15 show the sensitivity analysis results for W6, and Tables 4-16 to 4-19 show the same results for S4. As discussed in Chapter 2, the relative sensitivity is unitless, which provides a straightforward way to compare sensitivities over the selected input parameters that vary in their magnitudes in response to the same output variable. The following discussions are based on the relative sensitivity analysis results.

Figure 4-6 shows the relative sensitivities of total surface runoff to the six hydrologic input parameters for the 6-year simulation period for the calibration sites W6 and S4. The sensitivity of surface runoff to soil porosity at its increment of -50% from the base for site W6 is not provided in Figure 4-6 because the model run was terminated.
since the simulated water table dropped below the bottom of the soil profile. This indicates that these soil porosity values are out of the “reasonable range”. Results show that the two most sensitive parameters for surface runoff at W6 and S4 are crop coefficient and soil porosity. Runoff is more sensitive to crop coefficient for W6 while it is more sensitive to soil porosity for S4. Moreover, the third most sensitive parameter for surface runoff is restrictive layer hydraulic conductivity for both sites. The sensitivities of runoff to the rest of the selected hydrologic parameters are not significantly different from one another. It should be noted that the sensitivity of surface runoff to both crop coefficient and soil porosity are asymmetric for both sites compared with those of the rest of the parameters. In general, surface runoff shows similar sensitivity to these hydrologic parameters at both sites.

Figure 4-7 shows the relative sensitivities of maximum water table depth to the same selected hydrologic parameters at both sites. Maximum depressional storage is not shown since maximum water table depth is not sensitive to this parameter. It should be noted that the magnitude of sensitivities of maximum water table depth is significantly smaller than those for total surface runoff for all parameters at both sites. This is likely due to the fact that response times for subsurface water movement are much slower than for surface water movement. Results indicate that maximum water table depth is most sensitive to soil porosity for W6, while it is most sensitive to crop coefficient for S4. Note that the sensitivity of maximum water table depth to the crop coefficient is quite asymmetric for S4. Also, it is very interesting that maximum water table depth is significantly more sensitive to the wilting point for S4 than for W6. This is likely because S4 has relatively smaller soil porosity values than W6 (see Tables 4-6 and 4-7),
which implies less water availability in the soil profile of S4 for hydrological processes such as ET. An increase or decrease in wilting point could affect the amount of water available for ET. The remaining parameters, saturated hydraulic conductivity and restrictive layer hydraulic conductivity show quite similar symmetric sensitivity patterns for both sites.

The sensitivity tests of total surface runoff and maximum water table depth to the hydrologic input parameters demonstrate that the most sensitive hydrologic input parameters are those that represent physical properties that directly affect the soil water budget in a storage-limited hydrologic system, i.e., crop coefficient, soil porosity, and restrictive layer hydraulic conductivity. Furthermore, the sensitivities of both total surface runoff and maximum water table depth to the changes in these hydrologic parameters do not have the same magnitudes.

Together with the hydrologic input parameters, several nutrient parameters were selected to test the sensitivity of the total P and N load responses to the changes in these parameters. As shown in Figure 4-8, the magnitude of sensitivities of the P load response to the selected hydrologic parameters is similar to that for total surface runoff for both sites. The crop coefficient and soil porosity appear to be the most sensitive parameters for the P loads for sites W6 and S4. Furthermore, the sensitivity of the P load to restrictive layer hydraulic conductivity is more significant than the rest of the hydrologic parameters for both sites. Among all of the selected nutrient parameters, the rainfall P concentration is the most sensitive nutrient parameter, followed by the active P, to the P load response for W6. On the contrary, there is little sensitivity of the P load response to the rainfall P concentration for S4. Instead, the stable P is the most sensitive parameter,
followed by the active P, to the P load response for site S4. Such a difference in sensitivity of rainfall P concentration very likely results from the extremely different background P values for the semi-improved pasture site W6 and the improved pasture site S4. Generally, for both sites the P load response shows similar sensitivity patterns to hydrologic parameters as total surface runoff.

Figure 4-9 displays the relative sensitivities of the N load response to the selected parameters for both calibration sites. For site W6, the crop coefficient and restrictive layer conductivity appear to be the most sensitive hydrologic parameters and the porosity is also sensitive compared with the rest of the hydrologic parameters. Among all selected nutrient parameters, the N load response is most sensitive to the changes in rainfall N concentration. However, for site S4 the surface maximum depressional storage is the most sensitive parameter of all selected parameters although the crop coefficient, restrictive layer conductivity, and porosity are also sensitive parameters. The reason that N load shows high sensitivity to the surface maximum depressional storage for S4 is most likely from the combination of two aspects, reducing/increasing the surface maximum depressional storage leads to more/less water available for surface runoff and the nutrient-rich pasture S4 has relatively higher surface runoff N concentration. Unlike for W6, the N load response for S4 is not very sensitive to the rainfall N concentration. As discussed above for the P load response, this may be due to the fact that S4 is a nutrient-rich site and almost all nutrient pools are much larger than those for W6. As a result, the rainfall nutrient concentrations may not be major factors in changing the N load response.

In general, it is hard to draw consistent conclusions from both calibration sites for these selected parameters because their sensitivities appear to be site-specific. This
implies that nonlinear relationships exist between these selected parameters and output variables, and that there may be interactions among the input parameters.

**Results and discussion**

The simulation results to be discussed include the annual water budgets conducted for the four selected pasture sites; and the continuous simulation of major output variables, including water table depth, surface runoff, P and N loads, and P and N concentrations for the two pairs of calibration/verification sites: W6/W7 and S4/S1. Daily time series plots as well as monthly and annual linear plots, and daily duration curves of these major output variables were evaluated. Annual and monthly statistics comparisons of the simulated versus observed results were calculated and compared with those calculated by FHANTM (Sims, 2004).

Annual summaries for rainfall, observed and simulated runoff, simulated lateral ground water flow, simulated ET, and simulated deep seepage are listed in Tables 4-20, 4-21, 4-22, and 4-23 for the four selected pasture sites. There was less rainfall for year 2000 than for the rest of the years during the simulation period over all selected sites. There was relatively more rainfall for years 2002 and 2003 for the winter pasture sites and for year 2002 for the summer pasture sites. The percentages in columns for rainfall, ET and deep seepage indicate the percent of annual rainfall that these hydrological components account for. These data shows that about 1-34% of annual rainfall converted to runoff, 9-13% to deep seepage, and the remainder to evapotranspiration. These statistics are quite close to the previous studies of pine-cypress flatwoods in the southeastern United States according to Riekerk and Korhnak (2000).

Figure 4-10 and Figure 4-11 display the continuous simulation of groundwater table depths for the calibration site W6 and verification site W7 from September 2000
through December 2003. Very good agreement on timing and trends are found between the predicted and observed water table depths for both sites W6 and W7, with slightly larger discrepancies during a long dry period approximately from October 2000 through March 2001. During this dry period, the observed water table is very sensitive to small rainfall inputs so that observed water table fluctuated more rapidly to the rainfall inputs than the model predictions. Additionally, it is obvious that the measured water tables did not reach the ground surface throughout the simulation period even during the heavy rainfall inputs when surface runoff occurred. This error may come from erroneous measuring of the ground surface elevations of wells, which may have been installed in low spots in the field and thus the surface elevations measured at such locations may not be an appropriate estimate of the surface elevations for the entire land segment.

The conclusions drawn from the winter pasture sites also apply to the simulation of groundwater table depths for the summer pasture sites S4 and S1 (see Figures 4-12 and 4-13). However, there is a better agreement between the predicted and observed water table depths when the soils get saturated for the site S4 than for the other three sites. The predicted water tables agree with the observed data better in the two calibration sites than in the two verification sites.

Figures 4-14 and 4-15 show the continuous simulation of surface runoff from July 1998 to December 2003 for the calibration site W6 and verification site W7. For both sites, the model responded fairly well to the rainfall events on both timing and trends, and also was able to capture some of the back flows that were caused when the water elevation in the downstream canal was higher than that in the pasture sites. Nevertheless, the model generally did not capture the peak runoff very well. A few possible reasons
may explain this. First, the ditches located inside the pastures are deeper than the area’s
ground surface elevation. Thus they can collect the surface water and result in runoff at
the outlet of the pasture even when no sheet flow occurs. The current version of the
model does not consider water movement in these ditches. In the model surface runoff
occurs only when surface water is ponded on the entire land segment. Second, the
observed runoff is instantaneously measured data while the predicted runoff is the daily
average value. Using a daily time step may computationally delay the transport of runoff
to a certain extent. For example, if rainfall events last only a few hours, the resulting
overland flow could reach the downstream flume in less than a day, especially if rainfall
occurs near the flume where the runoff was measured. In the model, runoff is only
transported between land segments once a day. Therefore, the simulated overland flow
could be delayed with a resulting flattened hydrograph.

Similar conclusions can be drawn for the summer pasture sites S4 and S1 (see
Figures 4-16 and 4-17). However, the magnitude of surface runoff in the summer
pastures is generally smaller than for the winter pastures, which reduces the discrepancy
in peak runoffs to a certain extent.

Figures 4-18 and 4-19 show the continuous simulation of P loads from July 1998
through December 2003 for W6 and W7, respectively. Similar to the surface runoff
simulation, the predicted P loads agree well with the observed P loads on timing and
trend, but the model underestimates the peak P loads. Since the load is the product of the
volume of surface runoff and P concentration, the underestimation of surface peak
runoffs, as discussed earlier, directly contributes to the under-predictions of P loads.
However, Figures 4-26 and 4-27 show that underestimation of P concentrations,
especially for those times when peak runoff was underestimated, is likely another contributor to the underestimation of peak P loads for winter pastures W6 and W7. Figures 4-20 and 4-21 display the continuous simulation of P loads from July 1998 through December 2003 for the two summer pasture sites S4 and S1, respectively. The conclusions from these figures are similar to those obtained for the winter pastures sites. However, the magnitude of the difference in the prediction of P peak load in these summer pastures is more significant than for the winter pastures due to the fact that the summer pastures have high background nutrients.

Figures 4-22 and 4-23 show the continuous simulation of N load from July 1998 through December 2003 for W6 and W7, respectively. The predicted N load for sites W6 and W7 agree fairly well with the observed N loads, but the model still underestimates the peak N loads as it did the P loads for these sites. Compared with the simulated N loads, the observed N loads show higher peaks and more variability. Likewise, the model underestimates, as seen in Figures 4-24 and 4-25, most of the peak observed N loads for the two summer pasture sites S4 and S1, respectively.

Figures 4-26 through 4-33 show the continuous simulation of surface runoff P and N concentrations for the four selected pasture sites. These figures were prepared to help understand the P and N load prediction errors. For winter site W6, both observed P and N concentrations have higher peaks and more variability than simulated as shown in Figures 4-26 and 4-28. However, the magnitude of both P and N concentrations for W7 as seen in Figures 4-27 and 4-29 is smaller than that for W6, which leads to less discrepancy. Compared with the winter pasture sites, the model performed much better in predicting the P concentrations for S4 and S1 with a better agreement between the
predictions and observations as shown in Figures 4-30 and 4-31. Nevertheless, the model generally overestimated the N concentrations for both summer pasture sites S4 and S1 as shown in Figures 4-32 and 4-33.

As discussed above, the underestimations or overestimations in P and N concentrations directly contribute to the prediction errors of the P and N loads. It should be noted that the measured concentration values were from water samples collected at certain moments and locations near the flumes of pasture sites, while the simulated concentration values are daily values which represent the surface water P and N concentrations over the entire land segment. In addition, lack of the nutrient input information may also contribute to the suboptimal predictions of P and N concentrations. Nevertheless, those simulation results imply that nutrient cycling algorithms need further improvement when sufficient and reliable nutrient data are available.

Judging the model performance solely on the visual observation of the time series simulation can be subjective, especially when the simulation period spans multiple years. In order to quantify the model performance, a few statistics, including bias, RE, RMSE, CV, R², and NS as introduced in Chapter 2, were calculated using the predicted and observed data.

Tables 4-24, 4-25, 4-26, and 4-27 show the comparisons between the statistics obtained from the simulation results of the modified ACRU2000 model and the lumped FHANTM model performed by Sims (2004) for both the winter calibration site W6 and verification site W7. As shown in Tables 4-24 and 4-25, the statistics indicate that the modified ACRU2000 model is more accurate than FHANTM in predicting monthly and annual surface runoff and N load with smaller bias, RE, RMSE, and CV values obtained
from the modified ACRU2000 model than from FHANTM. All statistics except RE for the P load obtained from the modified model are also smaller than FHANTM and indicate a better prediction in P load. Both models overestimated monthly and annual surface runoff and N load with the positive bias and RE values. The modified model overestimated the P load while FHANTM underestimated the P load. Both models overestimated the N load. Smaller RMSE and CV values over all predicted output variables from the modified ACRU2000 indicate that the modified model generally performed better than FHANTM. For W6, the monthly CV values are generally greater than 1.0, which indicates that the model is adequate for screening purpose for monthly predictions (Hedden, 1996). The annual CV values are all less than one indicating the model is accurate enough to be used for site-specific application for annual predictions.

Similar conclusions regarding the monthly and annual statistics can be applied to surface runoff and P load (see Tables 4-26 and 4-27) for the verification site W7 as well drawn for calibration site W6. Both models performed similarly in predicting the N load with quite good statistics. Unlike for W6, the modified model underestimated surface runoff, and P and N loads. FHANTM overestimated the runoff but underestimated the P and N loads. The monthly and annual CV values for runoff indicate the model can be used for site specific monthly and annual predictions of runoff. The CV value for the P and N loads indicate that the model can only be used for screening application at the monthly level, but can be used for site specific application at the annual level. Overall, the comparison of statistics between the two models indicates that the modified ACRU2000 performed better than FHANTM for both winter sites according to the monthly and annual predictions.
No statistics for the water table depths were obtained for the FHANTM simulation. For the modified ACRU2000 model, the monthly NS value of 0.93 and annual NS of 0.96 for the calibration site W6, and the monthly NS of 0.81 and annual NS of 0.86 for the verification site indicate a very good overall performance in predicting water table depths. CV values for both sites for both monthly and annual predictions indicate that the model can be used for site-specific application in predicting the water table depth.

Comparing the statistics between the winter calibration and verification sites, Tables 4-20 through 4-23 show that the model performed slightly better in predicting surface runoff for the verification site with smaller bias, RE, RMSE, CV values and higher R² and NS value for the verification site than the calibration site. For the other three output variables, the model performed better for the calibration site than for the verification site with smaller bias, RE, RMSE, CV values and higher R² and NS values for the calibration site. Since RE, CV, R² and NS are unitless, it is possible to compare the statistics over the output variables. Generally, the statistics indicate that the model performed better in predicting hydrologic variables than nutrient variables.

There are no statistics available from FHANTM for the summer pastures, thus the evaluation of model performance in the summer pastures was made by comparing the statistics (see Tables 4-28, 4-29, 4-30, and 4-31) with those from the winter pastures. As seen in Tables 4-28 and 4-29, the comparisons of monthly statistics for the two calibration sites W6 and S4 indicate the predictions of four output variables are slightly more biased for S4 than for W6 but the general model performance for both calibration sites are close. For both sites the model performed better in predicting the monthly P loads than in the monthly N loads. When comparing the annual statistics for these two
calibration sites, the bias for all predicted variables is more apparent for S4 than for W6. CV values for runoff, water table depth, and P load indicate that the model can be used for site-specific monthly and annual prediction of these variables. The annual CV values for all variables indicate the model can be used for site-specific annual prediction for all variables. For the two verification sites, W7 and S1, the comparison of monthly statistics (see Tables 4-26 and 4-27) indicates that the model performed better for runoff and water table depth for W7, but it underestimated both P and N loads for W7 and overestimated them for S1. The same conclusion can be drawn for both sites by comparing their annual statistics for these variables.

Overall, the model performed better for the calibration sites than for the verification sites, better for hydrologic outputs than for nutrient outputs, and better for winter pasture sites than for summer pasture sites. According to the CV values, the model can be used for site-specific annual prediction of both hydrologic and nutrient transport and should be used primarily for screening application at the monthly level.

Linear plots provide a good tool to examine the agreement between the simulated and observed data and to determine over what ranges these data agree more closely with each other. The monthly and annual linear plots for the four major output variables from the four selected pasture sites are provided in Figures 4-34 through 4-49. It should be noted that the \( R^2 \) values in the linear plots indicate the quality of the linear fit between data points, but do not necessarily indicate how well the simulated values agree with the observed values (i.e. the quality of the 1:1 line fit).

Excellent agreement between the monthly and annual surface runoff is shown in the linear plots for the winter pasture sites W6 and W7 in Figures 4-34 and 4-35. These data
fall fairly close to the 1:1 line that indicates a perfect fit. The monthly and annual linear plots of water table depths for W6 (see Figure 4-36) also indicate excellent model performance. However, slight underestimations of water table depths in the lower range were observed for the verification site W7 (see Figure 4-37). A fairly good agreement between the simulated and measured P loads are shown in Figure 4-38 for site W6, while significant underestimations of P load in the high range are shown in Figure 4-39 for site W7. This bias is primarily caused by two extreme points and most of the other points are scattered around the 1:1 line. These extreme points may result from the underestimations of the peak P loads as discussed earlier. As shown in Figure 4-40, the model predicted the monthly and annual N loads quite well for site W6 with some overestimations in the higher ranges. However, larger underestimation of N loads throughout the entire range of values was observed for site W7 as shown in Figure 4-41. Observed N loads for the verification W7 were obviously higher than those for the calibration site W6. This fact increased the difficulty of model calibration.

For the summer calibration site S4, the linear plot (see Figure 4-42) indicates a fairly good match between the simulated and observed monthly runoff and a general overestimation of annual runoff. A similar conclusion can be drawn from the linear plot (see Figure 4-43) for the verification site S1, but the bias is a slightly more pronounced than for S4. A good match is shown in the linear plot (see Figure 4-44) of monthly and annual water table depth for the calibration site S4, but larger underestimation of monthly and annual water table depth in the lower range were observed from the plot for S1 (see Figure 4-45). A fairly good agreement between the simulated and observed P loads is observed in the linear plot for site S4 (see Figure 4-46), while a slightly larger
underestimation in the upper range of the P loads was found for S1 (see Figure 4-47). For the N loads, the match between the simulated and observed data for S4 are quite good with a little underestimation at its upper range (see Figure 4-48). A larger bias in both upper and lower ranges was observed in the linear plot of N loads for S1 (see Figure 4-49).

Daily duration curves offer an alternative way to investigate the agreement between daily predicted and measured values, and particularly to determine over what range of values the simulated output variables of interest match their corresponding observations more closely. Figure 4-50 displays the daily duration curves of surface runoff and water table depth for the winter calibration site W6. The duration curve of surface runoff indicates that the simulated daily runoff agrees very well with the observed runoff throughout the simulation period. The duration curve of water table depths indicates that the simulated water table depths are greater than the observed values at the higher and middle range of water table depths, and less than the observed values in the lower middle range of water table depths. The duration curves for both P and N loads for the calibration site W6 (see Figure 4-51) are quite consistent except for high P and N loads when the model underpredicts the response. Figure 4-52 displays the daily duration curves of surface runoff and water table depth for the winter verification site W7. The duration curves for surface runoff for the site W7 show a very good match. However, the duration curve of water table depths for W7 shows significant discrepancies at the higher range of water table depth. As for W6, the duration curve for P and N load for W7 show that the model significantly underpredicts the observed load.
Figure 4-54 displays the daily duration curves of surface runoff and water table for the summer calibration site S4. The differences between the predicted runoff and observed runoff primarily exist at the higher and middle range of values. The model underestimates the higher range and overestimates the middle range but generally these differences are not very significant. Interestingly, the duration curve of the water table depth for the site S4 indicates that the model overpredicted the observed data from the middle to upper range and underpredicted the rest of the range, and the differences between the simulated and observed values are generally more significant in the overestimation range than in the underestimation range. Figure 4-55 shows the duration curves of P and N loads for the calibration site S4. The trends and timing of the duration curve for the P loads are similar to the previous ones for the winter pasture sites. However, the model obviously performed better in predicting the duration curve for N loads with those for P loads. Figure 4-56 illustrates the daily duration curves of surface runoff and water table depth for the summer verification site S1. Compared with the previous duration curves for surface runoff, the model performed better for S1, with a close match between the predicted surface runoff and measured runoffs throughout the entire range of values. The duration curve for the water table depth indicates that the model overestimated the water table through the entire simulation period with the predicted duration curve consistently above the observed one. Figure 4-57 shows the duration curves of P and N loads for the verification site S1. The conclusions for the P loads drawn from its duration curve (see Figure 4-57) are similar to the previous ones for the other three sites. However, a better match between the prediction and observation is observed at the lower range of P loads. Compared with the duration curve of N loads for
S4, the one for S1 is fairly good, with much closer agreement between the predicted and observed N loads throughout the entire simulation period.

In general, the model performance in predicting surface runoff and water table is better than for P and N loads for all the selected pasture sites. Furthermore, the model did a better job in predicting output variables for the two calibration sites W6 and S4 than for the two verification sites. This difference is particularly apparent in P and N loads, and could be due to several factors: first, nutrient predictions inherit the errors resulting from the hydrologic model; second, the number of nutrient observations are quite limited during the 6-year simulation period compared with the hydrologic observations, and therefore provide a smaller range of data for calibrating the nutrient parameters; third, the generally higher P and N loads observed in the verification sites than in the calibration sites increased the difficulty in model calibration; finally, insufficiency and unavailability of input data, such as limited N and P observations throughout the 6-year simulation period, may have led to biased simulations.

**Concluding Remarks**

In this chapter, a nutrient model capable of multi-directional spatial transport and transformations of N, P and conservative solute was developed based on the existing nutrient module ACRU-NP (Campbell et al., 2001) in the ACRU2000 modeling system.

In order to investigate the accuracy of the conservative solute transport component, a test using the hypothetical scenario introduced in Chapter 3 together with new solute input was conducted by comparing with the particle tracking model PMPATH (Chiang and Kinzelbach, 2005). The testing results indicate the solute transport predicted by ACRU2000 is in reasonable agreement with the predictions by PMPATH. Due to the constraints of PMPATH in simulating particles instead of solute concentrations, it is
difficult to quantitatively judge the performance of the conservative solute transport model in the modified ACRU2000.

To evaluate the complete performance of the nutrient model within the framework of the previously modified hydrologic model in Chapter 3, an application to beef cattle pastures in Buck Island Ranch, Lake Okeechobee Basin, Florida was conducted. A complete model testing procedure including model calibration, verification, and sensitivity analysis was conducted. The water budget for each selected site was also determined to investigate whether the simulated major hydrologic components fall in reasonable ranges by comparing with the literature values for similar regions. Statistics were calculated to quantitatively evaluate the model performance for both model calibration and verification. Two pairs of pasture sites were selected, which differ in stocking rotation schedule, soil texture, land cover, and management activities. Generally, the predicted monthly and annual surface runoff, water table depth, and P and N loads are fairly promising in all these pastures. The model performance is better in predicting runoff and water table depth than P and N loads, better for the calibration sites than for the verification sites, and better for the winter pasture sites than for the summer sites.

The sensitivity analyses demonstrate that crop coefficient, porosity and restrictive layer hydraulic conductivity are the most sensitive input parameters for hydrologic responses among all selected hydrologic inputs, and they are also sensitive parameters for both P and N load responses. However, the sensitivities of nutrient parameters are site-specific due to different soil texture and background nutrients. The winter pasture sites have low background nutrients in soils, and therefore P and N loads are most sensitive to
rainfall P and N concentrations, respectively. On the contrary, the summer pasture sites have high background soil nutrient concentrations and the analyses results show that P and N loads are not sensitive to rainfall P and N concentrations, nutrient pools including active P and stable P for P loads and active N for N loads. Surprisingly, stocking and fertilizer rates are not sensitive parameters for either P or N responses. This seems to imply that the residual soil nutrient mass/concentrations are responsible for runoff nutrient outputs from these pasture sites, rather than agricultural activities such as stocking and fertilization. However, this experiment only lasted for a period of 6 years and the long-term impacts from stocking and fertilization may need to be investigated.

Additionally, one issue rising from the application to Buck Island is the insufficient nutrient data that was available to calibrate the nutrient parameters. Using instantaneously measured nutrient concentrations to calculate the nutrient loads may have caused bias of the observed loads. Furthermore, the limited number of nutrient observations may not adequately cover the entire range of load occurrences, which further challenges the calibration of nutrient parameters. Moreover, a common problem existed in the measured nutrient data for both pairs of pasture sites, i.e., for both calibration sites with cattle stocking, the observed nutrient loads were lower than those for their paired verification sites without cattle stocking. This makes the model calibration even more difficult when initial nutrient pools are not well known.

Methods for partitioning nutrients between the soil and water phases so that the soil nutrients can be transported between ponded surface water and soil water may need further improvement with respect to flatwoods soils. In order to do this, more accurate measured nutrient data are required. In addition, the nutrient loads carried by sediments
are not well considered in this multi-directional spatial simulation model since the sediment transport in Florida flatwoods soils is not as significant as flow transport. Nevertheless, it would enhance the model capabilities if improved sediment transport capacities were added in the future. Finally, the method for dealing with the nutrients released from the waste decomposition, the spatial distribution of cattle waste, and assuming only one plant species on each land segment is oversimplified. Future work should be done to represent these processes more accurately.

In general, it has been shown that this model is capable of simulating both hydrology and nutrient dynamics in field-scale catchments particularly for screening purposes. Thus, it can be used as a basis for coupling with a vegetation dynamic simulation model to form a more complete ecohydrological modeling system.
Table 4-2. List of stocking activities for pastures S1, S4, W6 and W7*.

<table>
<thead>
<tr>
<th>Timing</th>
<th>Management Practices</th>
<th>Stocking Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 21, 1998</td>
<td>Moved cattle into winter pastures</td>
<td>0  15  15  0</td>
</tr>
<tr>
<td>November 4, 1998</td>
<td>Moved cattle from winter into summer pastures</td>
<td>0  15  15  0</td>
</tr>
<tr>
<td>February 3, 1999</td>
<td>Moved cattle from summer into winter pastures</td>
<td>0  15  15  0</td>
</tr>
<tr>
<td>April 13, 1999</td>
<td>Moved cattle from winter into summer pastures</td>
<td>0  15  15  0</td>
</tr>
<tr>
<td>December 2-3, 1999</td>
<td>Moved cattle from summer into winter pastures</td>
<td>0  15  15  0</td>
</tr>
<tr>
<td>April 6, 2000</td>
<td>Moved cattle from winter into summer pastures</td>
<td>0  15  15  0</td>
</tr>
<tr>
<td>November 29, 2000</td>
<td>Moved cattle from summer into winter pastures</td>
<td>0  15  15  0</td>
</tr>
<tr>
<td>May 10, 2001</td>
<td>Moved cattle from winter into summer pastures</td>
<td>0  15  15  0</td>
</tr>
<tr>
<td>October 23, 2001</td>
<td>Moved cattle from summer into winter pastures</td>
<td>0  15  15  0</td>
</tr>
<tr>
<td>May 28, 2002</td>
<td>Moved cattle from winter into summer pastures</td>
<td>0  15  15  0</td>
</tr>
<tr>
<td>December 2, 2002</td>
<td>Moved cattle from winter into summer pastures</td>
<td>0  15  15  0</td>
</tr>
<tr>
<td>April 15, 2003</td>
<td>Moved cattle from winter into summer pastures</td>
<td>0  15  15  0</td>
</tr>
<tr>
<td>October 31, 2003</td>
<td>Moved cattle from summer into winter pastures</td>
<td>0  15  15  0</td>
</tr>
</tbody>
</table>

*Stocking information including dates, activities, and rates were obtained from the report (MAERC, 2004).

Table 4-3. List of fertilization activities for pastures S1 and S4*.

<table>
<thead>
<tr>
<th>Timing</th>
<th>Management Practices</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 1-9, 2000</td>
<td>Applied ammonium nitrogen fertilizer</td>
<td>56kg/ha</td>
</tr>
<tr>
<td>April 24, 2001</td>
<td>Applied ammonium nitrogen fertilizer</td>
<td>56kg/ha</td>
</tr>
<tr>
<td>March 28-29, 2003</td>
<td>Applied ammonium nitrogen fertilizer</td>
<td>56kg/ha</td>
</tr>
</tbody>
</table>

Fertilization activity information was obtained from the report (MAERC, 2004).

Table 4-4. List of burn activities for pastures S1, S4, W6 and W7*.

<table>
<thead>
<tr>
<th>Timing</th>
<th>Management Practices</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 24-24, 1998</td>
<td>Prescribed burn in all winter pastures</td>
</tr>
<tr>
<td>February 3, 1999</td>
<td>Prescribed burn in all summer pastures</td>
</tr>
<tr>
<td>March 1, 2000</td>
<td>Accidental fire occurred in W6</td>
</tr>
<tr>
<td>April 5, 2000</td>
<td>Accidental fire occurred in W7</td>
</tr>
<tr>
<td>February 11-12, 2002</td>
<td>Prescribed burn in all winter pastures</td>
</tr>
<tr>
<td>April 15-18, 2002</td>
<td>Prescribed burn in all summer pastures</td>
</tr>
</tbody>
</table>

Burn activity information was obtained from the report (MAERC, 2004).

Table 4-5. Percent of area occupied by different soil series and wetlands in selected summer and winter pastures.

<table>
<thead>
<tr>
<th>Pasture</th>
<th>Area (unit)</th>
<th>Mapped Soils (ha)</th>
<th>Felda Fine Sand (%)</th>
<th>Felda Fine Sand (%)</th>
<th>Bradenton Fine Sand (%)</th>
<th>Gator Muck (%)</th>
<th>Pineda Fine Sand (%)</th>
<th>Pineda Fine Sand (%)</th>
<th>Tequesta Muck (%)</th>
<th>Percentage of wetlands based on area of muck soils (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>22.0</td>
<td>21.6</td>
<td>67.0</td>
<td>11.3</td>
<td>0.7</td>
<td>3.1</td>
<td>17.9</td>
<td>20.9</td>
<td>7.1</td>
<td>20.9</td>
</tr>
<tr>
<td>S4</td>
<td>20.5</td>
<td>20.2</td>
<td>92.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W6</td>
<td>32.1</td>
<td>32.1</td>
<td>38.6</td>
<td>59.7</td>
<td>1.7</td>
<td>1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W7</td>
<td>30.2</td>
<td>30.2</td>
<td></td>
<td>1.2</td>
<td>94.5</td>
<td>4.3</td>
<td>1.7</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table is cited from MAERC (2004).
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>layer 1</td>
<td>layer 2</td>
</tr>
<tr>
<td>Soil layer depth</td>
<td>m</td>
<td>0.01</td>
</tr>
<tr>
<td>Bulk density</td>
<td>g/cc</td>
<td>1.22</td>
</tr>
<tr>
<td>Base saturation</td>
<td>%</td>
<td>67</td>
</tr>
<tr>
<td>Porosity</td>
<td>m/m</td>
<td>0.32</td>
</tr>
<tr>
<td>Wilting point</td>
<td>m/m</td>
<td>0.02</td>
</tr>
<tr>
<td>Field capacity</td>
<td>m/m</td>
<td>0.11</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>6.1</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity</td>
<td>m/s</td>
<td>3.3E-04</td>
</tr>
<tr>
<td>Res. conductivity</td>
<td>m/s</td>
<td>8.5E-10</td>
</tr>
<tr>
<td>Manning’s coefficient</td>
<td>m³/s</td>
<td>0.1</td>
</tr>
<tr>
<td>Brooks-Corey h</td>
<td>cm</td>
<td>1.63</td>
</tr>
<tr>
<td>Brooks-Corey λ</td>
<td></td>
<td>0.54</td>
</tr>
<tr>
<td>Brooks-Corey θ</td>
<td>m/m</td>
<td>0.02</td>
</tr>
<tr>
<td>Surface maximum depression storage</td>
<td>m</td>
<td>0.005</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td></td>
<td>0.70, 0.75, 0.80, 0.85, 0.90, 0.95, 1.0, 0.95, 0.90, 0.85, 0.80, 0.75 for 12 months</td>
</tr>
<tr>
<td>Silt content</td>
<td>%</td>
<td>0.9</td>
</tr>
<tr>
<td>Clay content</td>
<td>%</td>
<td>2.0</td>
</tr>
<tr>
<td>Mg content</td>
<td>mg/kg</td>
<td>49</td>
</tr>
<tr>
<td>AL content</td>
<td>mg/kg</td>
<td>466</td>
</tr>
<tr>
<td>Organic matter</td>
<td>%</td>
<td>2.17</td>
</tr>
<tr>
<td>Rainfall P &amp; N concentration</td>
<td>mg/l</td>
<td></td>
</tr>
<tr>
<td>Stream nutrient concentration</td>
<td>mg/l</td>
<td>0.013</td>
</tr>
<tr>
<td>Labile P</td>
<td>kg/ha</td>
<td>0.009</td>
</tr>
<tr>
<td>Active P</td>
<td>kg/ha</td>
<td>0.99</td>
</tr>
<tr>
<td>Stable P</td>
<td>kg/ha</td>
<td>2.65</td>
</tr>
<tr>
<td>Organic humus P</td>
<td>kg/ha</td>
<td>2.21</td>
</tr>
<tr>
<td>Fresh organic P</td>
<td>kg/ha</td>
<td>0.005</td>
</tr>
<tr>
<td>Nitrate-N</td>
<td>kg/ha</td>
<td>0.001</td>
</tr>
<tr>
<td>Ammonium-N</td>
<td>kg/ha</td>
<td>0.002</td>
</tr>
<tr>
<td>Active N</td>
<td>kg/ha</td>
<td>7</td>
</tr>
<tr>
<td>Stable N</td>
<td>kg/ha</td>
<td>293</td>
</tr>
<tr>
<td>Fresh organic N</td>
<td>kg/ha</td>
<td>0.05</td>
</tr>
<tr>
<td>Residue biomass</td>
<td>kg/ha</td>
<td>10</td>
</tr>
<tr>
<td>Manure app. rate</td>
<td>tons/ha</td>
<td></td>
</tr>
<tr>
<td>Fertilizer rate</td>
<td>kg/ha</td>
<td></td>
</tr>
</tbody>
</table>

*Values are referred to Pineda fine sand in Carlisle et al. (1989); †Values are calibrated; ‡Values are initially estimated using the procedures described by Fraisse and Campbell (1997) and further calibrated; ‡Value is the calibrated restrictive layer hydraulic conductivity; and §value is estimated according to MAERC (2004).
Table 4-7. Model input parameters for the summer pastures S4 and S1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil layer depth</td>
<td>m</td>
<td>0.01 0.08 0.27 0.17 0.08 0.30 0.26 0.28 0.28 0.30</td>
</tr>
<tr>
<td>Bulk density</td>
<td>g/cc</td>
<td>1.29 1.29 1.55 1.59 1.64 1.52 1.66 1.66 1.66 1.66</td>
</tr>
<tr>
<td>Base saturation</td>
<td>%</td>
<td>14 14 27 38 69 86 82 99 99 99</td>
</tr>
<tr>
<td>Porosity</td>
<td>m/m</td>
<td>0.31 0.31 0.12 0.12 0.15 0.12 0.14 0.18 0.29 0.30</td>
</tr>
<tr>
<td>Wilting point</td>
<td>m/m</td>
<td>0.03 0.03 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.03</td>
</tr>
<tr>
<td>Field capacity</td>
<td>m/m</td>
<td>0.08 0.08 0.05 0.05 0.06 0.05 0.06 0.06 0.06 0.07</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>3.8 3.8 4.6 5.1 5.1 5.7 5.7 7.6 7.8 7.6</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity</td>
<td>m/s</td>
<td>1.27E-03 1.27E-03 1.44E-03 1.81E-03 2.35E-06 3.10E-06 3.25E-06 3.90E-06 3.90E-06 2.15E-05</td>
</tr>
<tr>
<td>Res. conductivity</td>
<td>m/s</td>
<td>8.5E-10</td>
</tr>
<tr>
<td>Manning’s coefficient</td>
<td>m^1/3/s</td>
<td>0.1</td>
</tr>
<tr>
<td>Brooks-Corey h</td>
<td>cm</td>
<td>1.43 1.43 2.14 1.02 9.89 13.6 4.59 3.47 3.47 10.2</td>
</tr>
<tr>
<td>Brooks-Corey λ</td>
<td>cm</td>
<td>0.56 0.56 0.56 0.46 0.63 0.48 0.44 0.45 0.47 0.63</td>
</tr>
<tr>
<td>Brooks-Corey θ</td>
<td>cm</td>
<td>0.02 0.02 0.02 0.02 0.02 0.04 0.07 0.03 0.02 0.04</td>
</tr>
<tr>
<td>Exponent for upward flux</td>
<td></td>
<td>3.68 3.68 3.68 3.38 3.89 3.44 3.32 3.35 3.41 3.89</td>
</tr>
<tr>
<td>Surface maximum depression storage</td>
<td>m</td>
<td>0.005</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td></td>
<td>0.70, 0.75, 0.80, 0.85, 0.90, 1.0, 0.95, 0.90, 0.85, 0.80, 0.75 for 12 months</td>
</tr>
<tr>
<td>Silt content</td>
<td>%</td>
<td>1.3 1.3 1.6 2.0 3.7 5.9 4.6 3.2 3.2 3.0</td>
</tr>
<tr>
<td>Clay content</td>
<td>%</td>
<td>1.1 1.1 0.3 0.6 5.2 15.5 4.6 3.1 3.1 5.6</td>
</tr>
<tr>
<td>Mg content</td>
<td>mg/kg</td>
<td>151 151 62 62 62 1302 1302 1302 1302 1302</td>
</tr>
<tr>
<td>AL content</td>
<td>mg/kg</td>
<td>119 119 6 6 6 62 62 62 62 62</td>
</tr>
<tr>
<td>Organic matter</td>
<td>%</td>
<td>2.29 2.29 0.17 0.12 0.31 0.14 0.05 0.12 0.12 0.10</td>
</tr>
<tr>
<td>Rainfall P &amp; N concentrations</td>
<td>mg/l</td>
<td>0.020 for nitrate N and 0.028 for labile P</td>
</tr>
<tr>
<td>Stream nutrient concentrations</td>
<td>mg/l</td>
<td>0.013 for nitrate N, 0.006 for ammonium N, and 0.008 for labile P</td>
</tr>
<tr>
<td>Labile P</td>
<td>kg/ha</td>
<td>0.636 10.81 0.90 0.85 0.40 1.506 1.305 1.406 1.406 1.506</td>
</tr>
<tr>
<td>Active P</td>
<td>kg/ha</td>
<td>140 2379 198 2612 288 506 196 127 127 152</td>
</tr>
<tr>
<td>Stable P</td>
<td>kg/ha</td>
<td>636 1081 900 1187 1308 2301 891 576 576 689</td>
</tr>
<tr>
<td>Organic humus P</td>
<td>kg/ha</td>
<td>689 1172 5630 5450 2650 8517 8061 8681 8681 9302</td>
</tr>
<tr>
<td>Fresh organic P</td>
<td>kg/ha</td>
<td>1.87 3.36 6.72  —  —  —  —  —  —  —</td>
</tr>
<tr>
<td>Nitrate-N</td>
<td>kg/ha</td>
<td>0.026 0.044 0.056 0.054 0.026 0.091 0.086 0.093 0.093 0.099</td>
</tr>
<tr>
<td>Ammonium-N</td>
<td>kg/ha</td>
<td>0.001 0.022 0.028 0.027 0.013 0.046 0.043 0.047 0.047 0.050</td>
</tr>
<tr>
<td>Active N</td>
<td>kg/ha</td>
<td>290 4934 1255 1216 590 1710 1619 1743 1743 1868</td>
</tr>
<tr>
<td>Stable N</td>
<td>kg/ha</td>
<td>1857 3957 8036 7785 3779 1094 1035 1115 1115 11952</td>
</tr>
<tr>
<td>Fresh organic N</td>
<td>kg/ha</td>
<td>1.33 22.6 17.8  —  —  —  —  —  —  —</td>
</tr>
<tr>
<td>Residue biomass</td>
<td>kg/ha</td>
<td>100 1700 1800  —  —  —  —  —  —  —</td>
</tr>
<tr>
<td>Manure app. rate</td>
<td>tons/ha</td>
<td>0.003475 tons/ha</td>
</tr>
<tr>
<td>Fertilizer rate</td>
<td>kg/ha</td>
<td>9.24 kg/ha for nitrate and 9.24 kg/ha for</td>
</tr>
</tbody>
</table>

*Values are referred to Felda fine sand in Carlisle et al. (1989); *Values are calibrated; *Values are initially estimated using the procedures described by Fraisse and Campbell (1997) and further calibrated; *Value is the calibrated restrictive layer hydraulic conductivity; and *value is estimated according to MAERC (2004).
Table 4-8. Selected hydrologic parameters for sensitivity analysis for W6.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>-50%</th>
<th>-10%</th>
<th>Base</th>
<th>10%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td></td>
<td>0.160</td>
<td>0.288</td>
<td>0.320</td>
<td>0.352</td>
<td>0.480</td>
</tr>
<tr>
<td>Layer 2</td>
<td></td>
<td>0.160</td>
<td>0.288</td>
<td>0.320</td>
<td>0.352</td>
<td>0.480</td>
</tr>
<tr>
<td>Layer 3</td>
<td></td>
<td>0.060</td>
<td>0.108</td>
<td>0.120</td>
<td>0.132</td>
<td>0.180</td>
</tr>
<tr>
<td>Layer 4</td>
<td></td>
<td>0.070</td>
<td>0.126</td>
<td>0.140</td>
<td>0.154</td>
<td>0.210</td>
</tr>
<tr>
<td>Layer 5</td>
<td>m/m</td>
<td>0.120</td>
<td>0.216</td>
<td>0.240</td>
<td>0.264</td>
<td>0.360</td>
</tr>
<tr>
<td>Layer 6</td>
<td></td>
<td>0.110</td>
<td>0.198</td>
<td>0.220</td>
<td>0.242</td>
<td>0.330</td>
</tr>
<tr>
<td>Layer 7</td>
<td></td>
<td>0.125</td>
<td>0.225</td>
<td>0.250</td>
<td>0.275</td>
<td>0.375</td>
</tr>
<tr>
<td>Layer 8</td>
<td></td>
<td>0.175</td>
<td>0.315</td>
<td>0.350</td>
<td>0.385</td>
<td>0.525</td>
</tr>
<tr>
<td>Layer 9</td>
<td></td>
<td>0.185</td>
<td>0.333</td>
<td>0.370</td>
<td>0.407</td>
<td>0.555</td>
</tr>
<tr>
<td>Porosity</td>
<td></td>
<td>0.010</td>
<td>0.018</td>
<td>0.020</td>
<td>0.022</td>
<td>0.030</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.010</td>
<td>0.018</td>
<td>0.020</td>
<td>0.022</td>
<td>0.030</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.005</td>
<td>0.009</td>
<td>0.010</td>
<td>0.011</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.010</td>
<td>0.018</td>
<td>0.020</td>
<td>0.022</td>
<td>0.030</td>
</tr>
<tr>
<td>Wilting point</td>
<td></td>
<td>0.020</td>
<td>0.036</td>
<td>0.040</td>
<td>0.044</td>
<td>0.060</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.020</td>
<td>0.036</td>
<td>0.040</td>
<td>0.044</td>
<td>0.060</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.015</td>
<td>0.027</td>
<td>0.030</td>
<td>0.033</td>
<td>0.045</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.030</td>
<td>0.054</td>
<td>0.060</td>
<td>0.066</td>
<td>0.090</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.035</td>
<td>0.063</td>
<td>0.070</td>
<td>0.077</td>
<td>0.105</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity</td>
<td>m/s×10^{-4}</td>
<td>1.65</td>
<td>2.97</td>
<td>3.30</td>
<td>3.63</td>
<td>4.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.65</td>
<td>2.97</td>
<td>3.30</td>
<td>3.63</td>
<td>4.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.15</td>
<td>3.87</td>
<td>4.30</td>
<td>4.73</td>
<td>6.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.20</td>
<td>3.96</td>
<td>4.40</td>
<td>4.84</td>
<td>6.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.65</td>
<td>1.17</td>
<td>1.30</td>
<td>1.43</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.65</td>
<td>1.17</td>
<td>1.30</td>
<td>1.43</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.80</td>
<td>1.44</td>
<td>1.60</td>
<td>1.76</td>
<td>2.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.115</td>
<td>0.207</td>
<td>0.230</td>
<td>0.253</td>
<td>0.345</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.034</td>
<td>0.060</td>
<td>0.067</td>
<td>0.074</td>
<td>0.101</td>
</tr>
<tr>
<td>Restrictive layer hydraulic conductivity</td>
<td>m/s×10^{-9}</td>
<td>0.425</td>
<td>0.765</td>
<td>0.850</td>
<td>0.935</td>
<td>1.28</td>
</tr>
<tr>
<td>Manning’s roughness coefficient</td>
<td>m^{1/3}/s</td>
<td>0.05</td>
<td>0.09</td>
<td>0.10</td>
<td>0.11</td>
<td>0.15</td>
</tr>
<tr>
<td>Surface maximum depressional storage</td>
<td>m×10^{-2}</td>
<td>0.25</td>
<td>0.45</td>
<td>0.50</td>
<td>0.55</td>
<td>0.75</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td></td>
<td>0.35</td>
<td>0.63</td>
<td>0.70</td>
<td>0.77</td>
<td>1.05</td>
</tr>
<tr>
<td>January</td>
<td></td>
<td>0.38</td>
<td>0.68</td>
<td>0.75</td>
<td>0.83</td>
<td>1.13</td>
</tr>
<tr>
<td>February</td>
<td></td>
<td>0.40</td>
<td>0.72</td>
<td>0.80</td>
<td>0.88</td>
<td>1.20</td>
</tr>
<tr>
<td>March</td>
<td></td>
<td>0.43</td>
<td>0.77</td>
<td>0.85</td>
<td>0.94</td>
<td>1.28</td>
</tr>
<tr>
<td>April</td>
<td></td>
<td>0.45</td>
<td>0.81</td>
<td>0.90</td>
<td>0.99</td>
<td>1.35</td>
</tr>
<tr>
<td>May</td>
<td></td>
<td>0.48</td>
<td>0.86</td>
<td>0.95</td>
<td>1.05</td>
<td>1.43</td>
</tr>
<tr>
<td>June</td>
<td></td>
<td>0.50</td>
<td>0.90</td>
<td>1.00</td>
<td>1.10</td>
<td>1.50</td>
</tr>
<tr>
<td>July</td>
<td></td>
<td>0.48</td>
<td>0.86</td>
<td>0.95</td>
<td>1.05</td>
<td>1.43</td>
</tr>
<tr>
<td>August</td>
<td></td>
<td>0.45</td>
<td>0.81</td>
<td>0.90</td>
<td>0.99</td>
<td>1.35</td>
</tr>
<tr>
<td>September</td>
<td></td>
<td>0.43</td>
<td>0.77</td>
<td>0.85</td>
<td>0.94</td>
<td>1.28</td>
</tr>
<tr>
<td>October</td>
<td></td>
<td>0.40</td>
<td>0.72</td>
<td>0.80</td>
<td>0.88</td>
<td>1.20</td>
</tr>
<tr>
<td>November</td>
<td></td>
<td>0.38</td>
<td>0.68</td>
<td>0.75</td>
<td>0.83</td>
<td>1.13</td>
</tr>
</tbody>
</table>
Table 4-9. Selected nutrient parameters for sensitivity analysis for W6.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Testing Range</th>
<th>-50%</th>
<th>-10%</th>
<th>Base</th>
<th>10%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall P concentration</td>
<td>mg/l</td>
<td></td>
<td>0.014</td>
<td>0.025</td>
<td>0.028</td>
<td>0.031</td>
<td>0.042</td>
</tr>
<tr>
<td></td>
<td>Layer 1</td>
<td>0.50</td>
<td>0.89</td>
<td>0.99</td>
<td>1.09</td>
<td>1.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 2</td>
<td>4.47</td>
<td>8.04</td>
<td>8.93</td>
<td>9.83</td>
<td>13.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 3</td>
<td>1.30</td>
<td>2.34</td>
<td>2.59</td>
<td>2.85</td>
<td>3.89</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 4</td>
<td>1.30</td>
<td>2.34</td>
<td>2.60</td>
<td>2.86</td>
<td>3.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 5</td>
<td>1.85</td>
<td>3.33</td>
<td>3.70</td>
<td>4.07</td>
<td>5.55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 6</td>
<td>1.77</td>
<td>3.19</td>
<td>3.55</td>
<td>3.90</td>
<td>5.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 7</td>
<td>1.17</td>
<td>2.10</td>
<td>2.33</td>
<td>2.56</td>
<td>3.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 8</td>
<td>15.27</td>
<td>27.48</td>
<td>30.53</td>
<td>33.58</td>
<td>45.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 9</td>
<td>6.99</td>
<td>12.58</td>
<td>13.98</td>
<td>15.38</td>
<td>20.97</td>
<td></td>
</tr>
<tr>
<td>Rainfall N concentration</td>
<td>mg/l</td>
<td></td>
<td>0.010</td>
<td>0.018</td>
<td>0.020</td>
<td>0.022</td>
<td>0.030</td>
</tr>
<tr>
<td></td>
<td>Layer 1</td>
<td>0.50</td>
<td>0.89</td>
<td>0.99</td>
<td>1.09</td>
<td>1.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 2</td>
<td>4.47</td>
<td>8.04</td>
<td>8.93</td>
<td>9.83</td>
<td>13.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 3</td>
<td>1.30</td>
<td>2.34</td>
<td>2.59</td>
<td>2.85</td>
<td>3.89</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 4</td>
<td>1.30</td>
<td>2.34</td>
<td>2.60</td>
<td>2.86</td>
<td>3.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 5</td>
<td>1.85</td>
<td>3.33</td>
<td>3.70</td>
<td>4.07</td>
<td>5.55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 6</td>
<td>1.77</td>
<td>3.19</td>
<td>3.55</td>
<td>3.90</td>
<td>5.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 7</td>
<td>1.17</td>
<td>2.10</td>
<td>2.33</td>
<td>2.56</td>
<td>3.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 8</td>
<td>15.27</td>
<td>27.48</td>
<td>30.53</td>
<td>33.58</td>
<td>45.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 9</td>
<td>6.99</td>
<td>12.58</td>
<td>13.98</td>
<td>15.38</td>
<td>20.97</td>
<td></td>
</tr>
<tr>
<td>Active P</td>
<td>kg/ha</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 1</td>
<td>1.32</td>
<td>2.38</td>
<td>2.65</td>
<td>2.91</td>
<td>3.97</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 2</td>
<td>11.91</td>
<td>21.44</td>
<td>23.82</td>
<td>26.21</td>
<td>35.74</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 3</td>
<td>3.46</td>
<td>6.23</td>
<td>6.92</td>
<td>7.61</td>
<td>10.38</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 4</td>
<td>3.47</td>
<td>6.25</td>
<td>6.94</td>
<td>7.64</td>
<td>10.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 5</td>
<td>4.93</td>
<td>8.88</td>
<td>9.87</td>
<td>10.85</td>
<td>14.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 6</td>
<td>4.73</td>
<td>8.52</td>
<td>9.47</td>
<td>10.41</td>
<td>14.20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 7</td>
<td>3.11</td>
<td>5.59</td>
<td>6.22</td>
<td>6.84</td>
<td>9.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 8</td>
<td>40.71</td>
<td>73.28</td>
<td>81.42</td>
<td>89.56</td>
<td>122.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 9</td>
<td>18.64</td>
<td>33.55</td>
<td>37.27</td>
<td>41.00</td>
<td>55.91</td>
<td></td>
</tr>
<tr>
<td>Stable P</td>
<td>kg/ha</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 1</td>
<td>1.10</td>
<td>1.99</td>
<td>2.21</td>
<td>2.43</td>
<td>3.31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 2</td>
<td>9.93</td>
<td>17.87</td>
<td>19.85</td>
<td>21.84</td>
<td>29.78</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 3</td>
<td>20.23</td>
<td>36.42</td>
<td>40.47</td>
<td>44.51</td>
<td>60.70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 4</td>
<td>38.14</td>
<td>68.65</td>
<td>76.27</td>
<td>83.90</td>
<td>114.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 5</td>
<td>17.38</td>
<td>31.28</td>
<td>34.76</td>
<td>38.23</td>
<td>52.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 6</td>
<td>17.59</td>
<td>31.67</td>
<td>35.19</td>
<td>38.71</td>
<td>52.78</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 7</td>
<td>9.71</td>
<td>17.49</td>
<td>19.43</td>
<td>21.37</td>
<td>29.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 8</td>
<td>44.87</td>
<td>80.76</td>
<td>89.73</td>
<td>98.70</td>
<td>134.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 9</td>
<td>41.24</td>
<td>74.24</td>
<td>82.49</td>
<td>90.74</td>
<td>123.73</td>
<td></td>
</tr>
<tr>
<td>Humus P</td>
<td>kg/ha</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 1</td>
<td>3.66</td>
<td>6.59</td>
<td>7.32</td>
<td>8.05</td>
<td>10.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 2</td>
<td>32.94</td>
<td>59.29</td>
<td>65.88</td>
<td>72.47</td>
<td>98.82</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 3</td>
<td>10.14</td>
<td>18.25</td>
<td>20.28</td>
<td>22.31</td>
<td>30.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 4</td>
<td>15.90</td>
<td>28.62</td>
<td>31.80</td>
<td>34.98</td>
<td>47.70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 5</td>
<td>7.25</td>
<td>13.04</td>
<td>14.49</td>
<td>15.94</td>
<td>21.74</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 6</td>
<td>7.34</td>
<td>13.20</td>
<td>14.67</td>
<td>16.14</td>
<td>22.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 7</td>
<td>4.05</td>
<td>7.29</td>
<td>8.10</td>
<td>8.91</td>
<td>12.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 8</td>
<td>18.71</td>
<td>33.67</td>
<td>37.41</td>
<td>41.15</td>
<td>56.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 9</td>
<td>17.20</td>
<td>30.95</td>
<td>34.39</td>
<td>37.83</td>
<td>51.59</td>
<td></td>
</tr>
<tr>
<td>Active N</td>
<td>kg/ha</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 1</td>
<td>146.5</td>
<td>263.7</td>
<td>293.0</td>
<td>322.3</td>
<td>439.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 2</td>
<td>1317.5</td>
<td>2371.5</td>
<td>2635.0</td>
<td>2898.5</td>
<td>3952.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 3</td>
<td>405.5</td>
<td>729.9</td>
<td>811.0</td>
<td>892.1</td>
<td>1216.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 4</td>
<td>636.0</td>
<td>1144.8</td>
<td>1272.0</td>
<td>1399.2</td>
<td>1908.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 5</td>
<td>290.0</td>
<td>522.0</td>
<td>580.0</td>
<td>638.0</td>
<td>870.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 6</td>
<td>293.5</td>
<td>528.3</td>
<td>587.0</td>
<td>645.7</td>
<td>880.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 7</td>
<td>162.0</td>
<td>291.6</td>
<td>324.0</td>
<td>356.4</td>
<td>486.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 8</td>
<td>748.0</td>
<td>1346.4</td>
<td>1496.0</td>
<td>1645.6</td>
<td>2244.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 9</td>
<td>688.0</td>
<td>1238.4</td>
<td>1376.0</td>
<td>1513.6</td>
<td>2064.0</td>
<td></td>
</tr>
<tr>
<td>Stable N</td>
<td>kg/ha</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Layer 1</td>
<td>0.00174</td>
<td>0.00313</td>
<td>0.00348</td>
<td>0.00382</td>
<td>0.00521</td>
<td></td>
</tr>
</tbody>
</table>
Table 4-10. Selected hydrologic parameters for sensitivity analysis for S4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Testing Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-50%</td>
</tr>
<tr>
<td>Layer 1</td>
<td></td>
<td>0.155</td>
</tr>
<tr>
<td>Layer 2</td>
<td></td>
<td>0.155</td>
</tr>
<tr>
<td>Layer 3</td>
<td></td>
<td>0.060</td>
</tr>
<tr>
<td>Layer 4</td>
<td></td>
<td>0.060</td>
</tr>
<tr>
<td>Layer 5</td>
<td></td>
<td>0.075</td>
</tr>
<tr>
<td>Layer 6</td>
<td></td>
<td>0.060</td>
</tr>
<tr>
<td>Layer 7</td>
<td></td>
<td>0.070</td>
</tr>
<tr>
<td>Layer 8</td>
<td></td>
<td>0.090</td>
</tr>
<tr>
<td>Layer 9</td>
<td></td>
<td>0.145</td>
</tr>
<tr>
<td>Layer 10</td>
<td></td>
<td>0.152</td>
</tr>
<tr>
<td>Porosity</td>
<td>m/m</td>
<td>0.015</td>
</tr>
<tr>
<td>Wilting point</td>
<td>m/m</td>
<td>0.64</td>
</tr>
<tr>
<td>Saturated hydraulic</td>
<td>m/s×10⁻³</td>
<td>0.0012</td>
</tr>
<tr>
<td>conductivity</td>
<td></td>
<td>0.0016</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0016</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0019</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0019</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0108</td>
</tr>
<tr>
<td>Restrictive layer hydraulic</td>
<td>m/s×10⁻⁹</td>
<td>0.425</td>
</tr>
<tr>
<td>Manning’s roughness coefficient</td>
<td>m³/s¹/³</td>
<td>0.05</td>
</tr>
<tr>
<td>Surface maximum depressional storage</td>
<td>m×10⁻²</td>
<td>0.25</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td></td>
<td>January</td>
</tr>
<tr>
<td></td>
<td></td>
<td>February</td>
</tr>
<tr>
<td></td>
<td></td>
<td>March</td>
</tr>
<tr>
<td></td>
<td></td>
<td>April</td>
</tr>
<tr>
<td></td>
<td></td>
<td>May</td>
</tr>
<tr>
<td></td>
<td></td>
<td>June</td>
</tr>
<tr>
<td></td>
<td></td>
<td>July</td>
</tr>
<tr>
<td></td>
<td></td>
<td>August</td>
</tr>
<tr>
<td></td>
<td></td>
<td>September</td>
</tr>
<tr>
<td></td>
<td></td>
<td>October</td>
</tr>
<tr>
<td></td>
<td></td>
<td>November</td>
</tr>
<tr>
<td></td>
<td></td>
<td>December</td>
</tr>
<tr>
<td>Parameters</td>
<td>Unit</td>
<td>-50%</td>
</tr>
<tr>
<td>-----------------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Rainfall P concentration</td>
<td>mg/l</td>
<td>0.014</td>
</tr>
<tr>
<td>Rainfall N concentration</td>
<td>mg/l</td>
<td>0.010</td>
</tr>
<tr>
<td>Active P</td>
<td>kg/ha</td>
<td></td>
</tr>
<tr>
<td>Layer 1</td>
<td></td>
<td>7.0</td>
</tr>
<tr>
<td>Layer 2</td>
<td></td>
<td>1189.3</td>
</tr>
<tr>
<td>Layer 3</td>
<td></td>
<td>99</td>
</tr>
<tr>
<td>Layer 4</td>
<td></td>
<td>1306.2</td>
</tr>
<tr>
<td>Layer 5</td>
<td></td>
<td>143</td>
</tr>
<tr>
<td>Layer 6</td>
<td></td>
<td>253</td>
</tr>
<tr>
<td>Layer 7</td>
<td></td>
<td>98</td>
</tr>
<tr>
<td>Layer 8</td>
<td></td>
<td>63.3</td>
</tr>
<tr>
<td>Layer 9</td>
<td></td>
<td>63.3</td>
</tr>
<tr>
<td>Layer 10</td>
<td></td>
<td>75.8</td>
</tr>
<tr>
<td>Stable P</td>
<td>kg/ha</td>
<td></td>
</tr>
<tr>
<td>Layer 1</td>
<td></td>
<td>318</td>
</tr>
<tr>
<td>Layer 2</td>
<td></td>
<td>5406.0</td>
</tr>
<tr>
<td>Layer 3</td>
<td></td>
<td>450</td>
</tr>
<tr>
<td>Layer 4</td>
<td></td>
<td>5937.3</td>
</tr>
<tr>
<td>Layer 5</td>
<td></td>
<td>654</td>
</tr>
<tr>
<td>Layer 6</td>
<td></td>
<td>287</td>
</tr>
<tr>
<td>Layer 7</td>
<td></td>
<td>287</td>
</tr>
<tr>
<td>Layer 8</td>
<td></td>
<td>75.8</td>
</tr>
<tr>
<td>Layer 9</td>
<td></td>
<td>75.8</td>
</tr>
<tr>
<td>Layer 10</td>
<td></td>
<td>344.5</td>
</tr>
<tr>
<td>Humus P</td>
<td>kg/ha</td>
<td></td>
</tr>
<tr>
<td>Layer 1</td>
<td></td>
<td>344.5</td>
</tr>
<tr>
<td>Layer 2</td>
<td></td>
<td>5860.0</td>
</tr>
<tr>
<td>Layer 3</td>
<td></td>
<td>2815.0</td>
</tr>
<tr>
<td>Layer 4</td>
<td></td>
<td>2725.0</td>
</tr>
<tr>
<td>Layer 5</td>
<td></td>
<td>1325.0</td>
</tr>
<tr>
<td>Layer 6</td>
<td></td>
<td>4258.5</td>
</tr>
<tr>
<td>Layer 7</td>
<td></td>
<td>4030.5</td>
</tr>
<tr>
<td>Layer 8</td>
<td></td>
<td>4340.5</td>
</tr>
<tr>
<td>Layer 9</td>
<td></td>
<td>4340.5</td>
</tr>
<tr>
<td>Layer 10</td>
<td></td>
<td>4651.0</td>
</tr>
<tr>
<td>Active N</td>
<td>kg/ha</td>
<td></td>
</tr>
<tr>
<td>Layer 1</td>
<td></td>
<td>145.1</td>
</tr>
<tr>
<td>Layer 2</td>
<td></td>
<td>2467.1</td>
</tr>
<tr>
<td>Layer 3</td>
<td></td>
<td>627.8</td>
</tr>
<tr>
<td>Layer 4</td>
<td></td>
<td>608.2</td>
</tr>
<tr>
<td>Layer 5</td>
<td></td>
<td>295.2</td>
</tr>
<tr>
<td>Layer 6</td>
<td></td>
<td>855.0</td>
</tr>
<tr>
<td>Layer 7</td>
<td></td>
<td>871.5</td>
</tr>
<tr>
<td>Layer 8</td>
<td></td>
<td>871.5</td>
</tr>
<tr>
<td>Layer 9</td>
<td></td>
<td>871.5</td>
</tr>
<tr>
<td>Layer 10</td>
<td></td>
<td>933.8</td>
</tr>
<tr>
<td>Stable N</td>
<td>kg/ha</td>
<td></td>
</tr>
<tr>
<td>Layer 1</td>
<td></td>
<td>928.5</td>
</tr>
<tr>
<td>Layer 2</td>
<td></td>
<td>15789.8</td>
</tr>
<tr>
<td>Layer 3</td>
<td></td>
<td>4017.8</td>
</tr>
<tr>
<td>Layer 4</td>
<td></td>
<td>3892.5</td>
</tr>
<tr>
<td>Layer 5</td>
<td></td>
<td>1889.3</td>
</tr>
<tr>
<td>Layer 6</td>
<td></td>
<td>5472.0</td>
</tr>
<tr>
<td>Layer 7</td>
<td></td>
<td>5179.5</td>
</tr>
<tr>
<td>Layer 8</td>
<td></td>
<td>5577.8</td>
</tr>
<tr>
<td>Layer 9</td>
<td></td>
<td>5577.8</td>
</tr>
<tr>
<td>Layer 10</td>
<td></td>
<td>5976.0</td>
</tr>
<tr>
<td>Stocking rate</td>
<td>tons/ha</td>
<td>0.00174</td>
</tr>
<tr>
<td>Fertilizer rate</td>
<td>kg/ha</td>
<td>4.62</td>
</tr>
</tbody>
</table>
Table 4-12. Sensitivities of total surface runoff of the selected input parameters throughout the simulation period for the calibration site W6.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sensitivity [m³/day]</th>
<th>Relative sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-50%</td>
<td>-10%</td>
</tr>
<tr>
<td>Porosity</td>
<td>-**</td>
<td>49087</td>
</tr>
<tr>
<td>Wilting point</td>
<td>43219</td>
<td>44920</td>
</tr>
<tr>
<td>SatK*</td>
<td>47330</td>
<td>45674</td>
</tr>
<tr>
<td>ResK*</td>
<td>52953</td>
<td>46816</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td>79106</td>
<td>50939</td>
</tr>
<tr>
<td>SurfStorage</td>
<td>46497</td>
<td>45549</td>
</tr>
</tbody>
</table>

SatK= saturated hydraulic conductivity; ResK= restrictive layer hydraulic conductivity; surfStorage= surface storage.

** Not applicable.

Table 4-13. Sensitivities of maximum water table to the selected input parameters depth throughout the simulation period for the calibration site W6.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sensitivity [m]</th>
<th>Relative sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-50%</td>
<td>-10%</td>
</tr>
<tr>
<td>Porosity</td>
<td>-**</td>
<td>1.7201</td>
</tr>
<tr>
<td>Wilting point</td>
<td>1.7060</td>
<td>1.6919</td>
</tr>
<tr>
<td>SatK*</td>
<td>1.6120</td>
<td>1.6781</td>
</tr>
<tr>
<td>ResK*</td>
<td>1.6409</td>
<td>1.6808</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td>1.5832</td>
<td>1.6785</td>
</tr>
</tbody>
</table>

SatK= saturated hydraulic conductivity; ResK= restrictive layer hydraulic conductivity; surfStorage= surface storage.

** Not applicable.

Table 4-14. Sensitivities of total P loads to the selected input parameters throughout the simulation period for the calibration site W6.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sensitivity [kg/ha]</th>
<th>Relative sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-50%</td>
<td>-10%</td>
</tr>
<tr>
<td>Porosity</td>
<td>-**</td>
<td>3.7889</td>
</tr>
<tr>
<td>Wilting point</td>
<td>3.5866</td>
<td>3.4808</td>
</tr>
<tr>
<td>SatK*</td>
<td>3.6739</td>
<td>3.5376</td>
</tr>
<tr>
<td>ResK*</td>
<td>4.1091</td>
<td>3.6283</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td>6.1475</td>
<td>3.9578</td>
</tr>
<tr>
<td>SurfStorage</td>
<td>3.6710</td>
<td>3.5498</td>
</tr>
<tr>
<td>Rainfall P</td>
<td>2.3879</td>
<td>3.2704</td>
</tr>
<tr>
<td>Active P</td>
<td>2.8997</td>
<td>3.3863</td>
</tr>
<tr>
<td>Stable P</td>
<td>3.5016</td>
<td>3.5097</td>
</tr>
</tbody>
</table>

SatK= saturated hydraulic conductivity; ResK= restrictive layer hydraulic conductivity; surfStorage= surface storage.

** Not applicable.

Table 4-15. Sensitivities of total N loads to the selected input parameters throughout the simulation period for the calibration site W6.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sensitivity [kg/ha]</th>
<th>Relative sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-50%</td>
<td>-10%</td>
</tr>
<tr>
<td>Porosity</td>
<td>-**</td>
<td>5.6473</td>
</tr>
<tr>
<td>Wilting point</td>
<td>5.3777</td>
<td>5.6044</td>
</tr>
<tr>
<td>SatK*</td>
<td>5.9961</td>
<td>5.7681</td>
</tr>
<tr>
<td>ResK*</td>
<td>8.1360</td>
<td>6.1048</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td>10.695</td>
<td>6.4786</td>
</tr>
<tr>
<td>SurfStorage</td>
<td>6.3471</td>
<td>5.7939</td>
</tr>
<tr>
<td>Rainfall N</td>
<td>3.4234</td>
<td>5.2452</td>
</tr>
<tr>
<td>Active N</td>
<td>5.3280</td>
<td>5.6473</td>
</tr>
</tbody>
</table>

SatK= saturated hydraulic conductivity; ResK= restrictive layer hydraulic conductivity; surfStorage= surface storage.

** Not applicable.
### Table 4-16. Sensitivities of total surface runoff to the selected input parameters throughout the simulation period for the calibration site S4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sensitivity [m³/day]</th>
<th>Relative sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>514486</td>
<td>401221</td>
</tr>
<tr>
<td>Wilting point</td>
<td>353052</td>
<td>372690</td>
</tr>
<tr>
<td>SatK*</td>
<td>392162</td>
<td>395768</td>
</tr>
<tr>
<td>ResK*</td>
<td>413582</td>
<td>384527</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td>511687</td>
<td>398875</td>
</tr>
<tr>
<td>SurfStorage</td>
<td>389419</td>
<td>379832</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sensitivity [m³/day]</th>
<th>Relative sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50%</td>
<td>377071</td>
<td>356119</td>
</tr>
<tr>
<td>-10%</td>
<td>329779</td>
<td>0.73</td>
</tr>
<tr>
<td>Base</td>
<td>0.64</td>
<td>0.00</td>
</tr>
<tr>
<td>10%</td>
<td>0.00</td>
<td>-0.05</td>
</tr>
<tr>
<td>50%</td>
<td>0.46</td>
<td>0.00</td>
</tr>
</tbody>
</table>

*SatK*= saturated hydraulic conductivity; *ResK*= restrictive layer hydraulic conductivity; *surfStorage*= surface storage.

### Table 4-17. Sensitivities of maximum water table to the selected input parameters depth throughout the simulation period for the calibration site S4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sensitivity [m]</th>
<th>Relative sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>1.6549</td>
<td>1.5889</td>
</tr>
<tr>
<td>Wilting point</td>
<td>1.6732</td>
<td>1.5905</td>
</tr>
<tr>
<td>SatK*</td>
<td>1.5188</td>
<td>1.5662</td>
</tr>
<tr>
<td>ResK*</td>
<td>1.5295</td>
<td>1.5613</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td>1.4023</td>
<td>1.5650</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sensitivity [m]</th>
<th>Relative sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50%</td>
<td>1.5751</td>
<td>1.5598</td>
</tr>
<tr>
<td>-10%</td>
<td>1.5575</td>
<td>0.10</td>
</tr>
<tr>
<td>Base</td>
<td>0.00</td>
<td>-0.10</td>
</tr>
<tr>
<td>10%</td>
<td>0.00</td>
<td>-0.05</td>
</tr>
<tr>
<td>50%</td>
<td>0.00</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

*SatK*= saturated hydraulic conductivity; *ResK*= restrictive layer hydraulic conductivity; *surfStorage*= surface storage.

### Table 4-18. Sensitivities of total P loads to the selected input parameters throughout the simulation period for the calibration site S4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sensitivity [kg/ha]</th>
<th>Relative sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>21.611</td>
<td>16.856</td>
</tr>
<tr>
<td>Wilting point</td>
<td>14.717</td>
<td>15.674</td>
</tr>
<tr>
<td>SatK*</td>
<td>16.433</td>
<td>15.949</td>
</tr>
<tr>
<td>ResK*</td>
<td>17.325</td>
<td>16.153</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td>21.189</td>
<td>16.712</td>
</tr>
<tr>
<td>SurfStorage</td>
<td>16.630</td>
<td>16.062</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sensitivity [kg/ha]</th>
<th>Relative sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50%</td>
<td>15.847</td>
<td>14.986</td>
</tr>
<tr>
<td>-10%</td>
<td>12.215</td>
<td>0.73</td>
</tr>
<tr>
<td>Base</td>
<td>0.64</td>
<td>0.00</td>
</tr>
<tr>
<td>10%</td>
<td>0.00</td>
<td>-0.54</td>
</tr>
<tr>
<td>50%</td>
<td>0.46</td>
<td>-0.46</td>
</tr>
</tbody>
</table>

*SatK*= saturated hydraulic conductivity; *ResK*= restrictive layer hydraulic conductivity; *surfStorage*= surface storage.

### Table 4-19. Sensitivities of total N loads to the selected input parameters throughout the simulation period for the calibration site S4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sensitivity [kg/ha]</th>
<th>Relative sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>9.9295</td>
<td>8.3176</td>
</tr>
<tr>
<td>Wilting point</td>
<td>7.6516</td>
<td>7.9431</td>
</tr>
<tr>
<td>SatK*</td>
<td>8.3318</td>
<td>8.0638</td>
</tr>
<tr>
<td>ResK*</td>
<td>9.8029</td>
<td>8.3213</td>
</tr>
<tr>
<td>Crop coefficient</td>
<td>14.024</td>
<td>8.6844</td>
</tr>
<tr>
<td>SurfStorage</td>
<td>16.692</td>
<td>8.7898</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sensitivity [kg/ha]</th>
<th>Relative sensitivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50%</td>
<td>8.0015</td>
<td>7.7373</td>
</tr>
<tr>
<td>-10%</td>
<td>7.3497</td>
<td>0.48</td>
</tr>
<tr>
<td>Base</td>
<td>0.40</td>
<td>0.00</td>
</tr>
<tr>
<td>10%</td>
<td>0.00</td>
<td>-0.33</td>
</tr>
<tr>
<td>50%</td>
<td>0.16</td>
<td>-0.16</td>
</tr>
</tbody>
</table>

*SatK*= saturated hydraulic conductivity; *ResK*= restrictive layer hydraulic conductivity; *surfStorage*= surface storage.
Table 4-20. Annual water budget for the calibration site W6.

<table>
<thead>
<tr>
<th>Year</th>
<th>Obs. R (^1)</th>
<th>Obs. RO (^2)</th>
<th>Sim. RO (^3)</th>
<th>Sim. LG (^4)</th>
<th>Sim. ET (^5)</th>
<th>Sim. DS (^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>138.05</td>
<td>20.90</td>
<td>35.24 (25.5%)</td>
<td>0.20</td>
<td>91.92 (62.0%)</td>
<td>17.19 (12.5%)</td>
</tr>
<tr>
<td>1999</td>
<td>114.82</td>
<td>15.12</td>
<td>7.32 (6.4%)</td>
<td>-0.22</td>
<td>96.80 (81.3%)</td>
<td>14.17 (12.3%)</td>
</tr>
<tr>
<td>2000</td>
<td>75.63</td>
<td>0.57</td>
<td>1.09 (1.4%)</td>
<td>-0.24</td>
<td>73.75 (85.9%)</td>
<td>9.58 (12.7%)</td>
</tr>
<tr>
<td>2001</td>
<td>135.14</td>
<td>24.17</td>
<td>31.14 (23.0%)</td>
<td>-0.22</td>
<td>83.46 (67.2%)</td>
<td>13.17 (9.7%)</td>
</tr>
<tr>
<td>2002</td>
<td>151.08</td>
<td>25.29</td>
<td>31.88 (21.1%)</td>
<td>-0.03</td>
<td>90.69 (67.9%)</td>
<td>16.58 (11.0%)</td>
</tr>
<tr>
<td>2003</td>
<td>156.52</td>
<td>46.58</td>
<td>34.70 (22.2%)</td>
<td>-0.08</td>
<td>113.64 (66.3%)</td>
<td>17.98 (11.0%)</td>
</tr>
</tbody>
</table>

\(^1\)Observed rainfall [cm]; \(^2\)Observed runoff [cm]; \(^3\)Simulated runoff [cm]; \(^4\)Simulated lateral groundwater flow [cm]; \(^5\)Evapotranspiration [cm]; \(^6\)Deep seepage [cm]; and \(^7\)Percentages indicate the share each hydrologic component accounts for in rainfall input, respectively.

Table 4-21. Annual water budget for the verification site W7.

<table>
<thead>
<tr>
<th>Year</th>
<th>Obs. R (^1)</th>
<th>Obs. RO (^2)</th>
<th>Sim. RO (^3)</th>
<th>Sim. LG (^4)</th>
<th>Sim. ET (^5)</th>
<th>Sim. DS (^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>138.05</td>
<td>24.33</td>
<td>35.90 (26.0%)</td>
<td>0.04</td>
<td>91.69 (61.6%)</td>
<td>17.13 (12.4%)</td>
</tr>
<tr>
<td>1999</td>
<td>114.82</td>
<td>14.77</td>
<td>7.65 (6.7%)</td>
<td>-0.81</td>
<td>96.83 (81.0%)</td>
<td>14.11 (12.3%)</td>
</tr>
<tr>
<td>2000</td>
<td>75.63</td>
<td>0.98</td>
<td>1.21 (1.6%)</td>
<td>-0.78</td>
<td>74.26 (85.7%)</td>
<td>9.63 (12.7%)</td>
</tr>
<tr>
<td>2001</td>
<td>135.14</td>
<td>32.06</td>
<td>30.93 (22.9%)</td>
<td>-0.78</td>
<td>83.80 (67.4%)</td>
<td>13.17 (9.7%)</td>
</tr>
<tr>
<td>2002</td>
<td>151.08</td>
<td>33.72</td>
<td>32.27 (21.4%)</td>
<td>-0.32</td>
<td>91.25 (67.7%)</td>
<td>16.53 (10.9%)</td>
</tr>
<tr>
<td>2003</td>
<td>156.52</td>
<td>45.65</td>
<td>35.75 (22.8%)</td>
<td>-0.61</td>
<td>113.15 (65.8%)</td>
<td>17.81 (11.4%)</td>
</tr>
</tbody>
</table>

\(^1\)Observed rainfall [cm]; \(^2\)Observed runoff [cm]; \(^3\)Simulated runoff [cm]; \(^4\)Simulated lateral groundwater flow [cm]; \(^5\)Evapotranspiration [cm]; \(^6\)Deep seepage [cm]; and \(^7\)Percentages indicate the share each hydrologic component accounts for in rainfall input, respectively.

Table 4-22. Annual water budget for the calibration site S4.

<table>
<thead>
<tr>
<th>Year</th>
<th>Obs. R (^1)</th>
<th>Obs. RO (^2)</th>
<th>Sim. RO (^3)</th>
<th>Sim. LG (^4)</th>
<th>Sim. ET (^5)</th>
<th>Sim. DS (^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>138.24</td>
<td>9.93</td>
<td>37.46 (27.1%)</td>
<td>0.93</td>
<td>92.63 (62.7%)</td>
<td>10.04 (10.2%)</td>
</tr>
<tr>
<td>1999</td>
<td>122.00</td>
<td>15.02</td>
<td>27.13 (22.2%)</td>
<td>0.36</td>
<td>84.03 (67.9%)</td>
<td>12.04 (9.9%)</td>
</tr>
<tr>
<td>2000</td>
<td>75.17</td>
<td>0.43</td>
<td>1.25 (1.7%)</td>
<td>-0.79</td>
<td>68.51 (85.0%)</td>
<td>10.03 (13.3%)</td>
</tr>
<tr>
<td>2001</td>
<td>127.34</td>
<td>23.78</td>
<td>42.48 (33.4%)</td>
<td>0.45</td>
<td>69.65 (58.0%)</td>
<td>10.96 (8.6%)</td>
</tr>
<tr>
<td>2002</td>
<td>143.53</td>
<td>26.51</td>
<td>45.62 (31.8%)</td>
<td>1.17</td>
<td>74.56 (59.3%)</td>
<td>12.79 (8.9%)</td>
</tr>
<tr>
<td>2003</td>
<td>134.30</td>
<td>19.95</td>
<td>31.10 (23.2%)</td>
<td>0.41</td>
<td>98.02 (66.9%)</td>
<td>13.32 (9.9%)</td>
</tr>
</tbody>
</table>

\(^1\)Observed rainfall [cm]; \(^2\)Observed runoff [cm]; \(^3\)Simulated runoff [cm]; \(^4\)Simulated lateral groundwater flow [cm]; \(^5\)Evapotranspiration [cm]; \(^6\)Deep seepage [cm]; and \(^7\)Percentages indicate the share each hydrologic component accounts for in rainfall input, respectively.

Table 4-23. Annual water budget for the verification site S1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Obs. R (^1)</th>
<th>Obs. RO (^2)</th>
<th>Sim. RO (^3)</th>
<th>Sim. LG (^4)</th>
<th>Sim. ET (^5)</th>
<th>Sim. DS (^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>138.24</td>
<td>8.11</td>
<td>37.66 (27.2%)</td>
<td>0.46</td>
<td>93.47 (62.7%)</td>
<td>13.91 (10%)</td>
</tr>
<tr>
<td>1999</td>
<td>122.00</td>
<td>8.16</td>
<td>27.53 (22.6%)</td>
<td>0.18</td>
<td>83.62 (67.7%)</td>
<td>11.92 (10%)</td>
</tr>
<tr>
<td>2000</td>
<td>75.17</td>
<td>-1.08</td>
<td>0.59 (0.8%)</td>
<td>-0.29</td>
<td>68.69 (86.0%)</td>
<td>9.92 (13%)</td>
</tr>
<tr>
<td>2001</td>
<td>127.34</td>
<td>25.60</td>
<td>43.26 (34.0%)</td>
<td>0.34</td>
<td>69.49 (57.4%)</td>
<td>10.93 (9%)</td>
</tr>
<tr>
<td>2002</td>
<td>143.53</td>
<td>27.35</td>
<td>46.28 (32.2%)</td>
<td>0.63</td>
<td>74.28 (59.0%)</td>
<td>12.61 (9%)</td>
</tr>
<tr>
<td>2003</td>
<td>134.30</td>
<td>14.75</td>
<td>31.37 (23.4%)</td>
<td>0.36</td>
<td>98.15 (66.9%)</td>
<td>13.15 (10%)</td>
</tr>
</tbody>
</table>

\(^1\)Observed rainfall [cm]; \(^2\)Observed runoff [cm]; \(^3\)Simulated runoff [cm]; \(^4\)Simulated lateral groundwater flow [cm]; \(^5\)Evapotranspiration [cm]; \(^6\)Deep seepage [cm]; and \(^7\)Percentages indicate the share each hydrologic component accounts for in rainfall input, respectively.
Table 4-24. Monthly statistics for the calibration site W6

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Runoff</th>
<th>Water Table Depth</th>
<th>P Load</th>
<th>N Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>0.05</td>
<td>0.86</td>
<td>78.36</td>
<td>-</td>
</tr>
<tr>
<td>RE</td>
<td>0.03</td>
<td>0.43</td>
<td>-0.06</td>
<td>-</td>
</tr>
<tr>
<td>RMSE</td>
<td>1.86</td>
<td>4.27</td>
<td>391.06</td>
<td>-</td>
</tr>
<tr>
<td>CV</td>
<td>1.01</td>
<td>2.14</td>
<td>-0.31</td>
<td>-</td>
</tr>
<tr>
<td>R²</td>
<td>0.81</td>
<td>-</td>
<td>0.94</td>
<td>-</td>
</tr>
<tr>
<td>NS</td>
<td>0.75</td>
<td>-</td>
<td>0.93</td>
<td>-</td>
</tr>
</tbody>
</table>

*Units of bias and RMSE for runoff and water table depth are cm and for P and N loads are kg/ha. The rest of statistics are unitless for all variables. **Indicate not calculated by Sims (2004).

Table 4-25. Annual statistics for the calibration site W6

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Runoff</th>
<th>Water Table Depth</th>
<th>P Load</th>
<th>N Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>0.56</td>
<td>10.30</td>
<td>940.32</td>
<td>-</td>
</tr>
<tr>
<td>RE</td>
<td>0.03</td>
<td>0.43</td>
<td>-0.06</td>
<td>-</td>
</tr>
<tr>
<td>RMSE</td>
<td>8.66</td>
<td>14.80</td>
<td>2487.80</td>
<td>-</td>
</tr>
<tr>
<td>CV</td>
<td>0.39</td>
<td>0.62</td>
<td>-0.17</td>
<td>-</td>
</tr>
<tr>
<td>R²</td>
<td>0.69</td>
<td>-</td>
<td>0.97</td>
<td>-</td>
</tr>
<tr>
<td>NS</td>
<td>0.67</td>
<td>-</td>
<td>0.96</td>
<td>-</td>
</tr>
</tbody>
</table>

*Units of bias and RMSE for runoff and water table depth are cm and for P and N loads are kg/ha. The rest of statistics are unitless for all variables. **Indicate not calculated by Sims (2004).

Table 4-26. Monthly statistics for the verification site W7

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Runoff</th>
<th>Water Table Depth</th>
<th>P Load</th>
<th>N Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>-0.18</td>
<td>0.54</td>
<td>291.11</td>
<td>-</td>
</tr>
<tr>
<td>RE</td>
<td>-0.09</td>
<td>0.24</td>
<td>-0.20</td>
<td>-</td>
</tr>
<tr>
<td>RMSE</td>
<td>1.59</td>
<td>4.26</td>
<td>677.99</td>
<td>-</td>
</tr>
<tr>
<td>CV</td>
<td>0.76</td>
<td>2.13</td>
<td>-0.46</td>
<td>-</td>
</tr>
<tr>
<td>R²</td>
<td>0.87</td>
<td>-</td>
<td>0.85</td>
<td>-</td>
</tr>
<tr>
<td>NS</td>
<td>0.86</td>
<td>-</td>
<td>0.81</td>
<td>-</td>
</tr>
</tbody>
</table>

*Units of bias and RMSE for runoff and water table depth are cm and for P and N loads are kg/ha. The rest of statistics are unitless for all variables. **Indicate not calculated by Sims (2004).

Table 4-27. Annual statistics for the verification site W7

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Runoff</th>
<th>Water Table Depth</th>
<th>P Load</th>
<th>N Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>-2.16</td>
<td>6.53</td>
<td>3493.32</td>
<td>-</td>
</tr>
<tr>
<td>RE</td>
<td>-0.09</td>
<td>0.24</td>
<td>-0.20</td>
<td>-</td>
</tr>
<tr>
<td>RMSE</td>
<td>5.68</td>
<td>14.75</td>
<td>5331.74</td>
<td>-</td>
</tr>
<tr>
<td>CV</td>
<td>0.22</td>
<td>0.61</td>
<td>-0.30</td>
<td>-</td>
</tr>
<tr>
<td>R²</td>
<td>0.87</td>
<td>-</td>
<td>0.93</td>
<td>-</td>
</tr>
<tr>
<td>NS</td>
<td>0.84</td>
<td>-</td>
<td>0.86</td>
<td>-</td>
</tr>
</tbody>
</table>

*Units of bias and RMSE for runoff and water table depth are cm and for P and N loads are kg/ha. The rest of statistics are unitless for all variables. **Indicate not calculated by Sims (2004).
Table 4-28. Monthly statistics for the calibration site S4

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Runoff</th>
<th>Water Table</th>
<th>P Load</th>
<th>N Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>0.21</td>
<td>159.04</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>RE</td>
<td>0.16</td>
<td>-0.12</td>
<td>0.23</td>
<td>0.36</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.99</td>
<td>472.46</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>CV</td>
<td>0.75</td>
<td>-0.36</td>
<td>0.91</td>
<td>1.32</td>
</tr>
<tr>
<td>R²</td>
<td>0.87</td>
<td>0.92</td>
<td>0.85</td>
<td>0.73</td>
</tr>
<tr>
<td>NS</td>
<td>0.85</td>
<td>0.89</td>
<td>0.82</td>
<td>0.68</td>
</tr>
</tbody>
</table>

*Units of bias and RMSE for runoff and water table depth are cm and for P and N loads are kg/ha. The rest of statistics are unitless for all variables.

Table 4-29. Annual statistics for the calibration site S4

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Runoff</th>
<th>Water Table</th>
<th>P Load</th>
<th>N Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>2.55</td>
<td>1908.44</td>
<td>0.24</td>
<td>0.14</td>
</tr>
<tr>
<td>RE</td>
<td>0.16</td>
<td>-0.12</td>
<td>0.23</td>
<td>0.36</td>
</tr>
<tr>
<td>RMSE</td>
<td>3.73</td>
<td>2969.41</td>
<td>0.31</td>
<td>0.18</td>
</tr>
<tr>
<td>CV</td>
<td>0.23</td>
<td>-0.19</td>
<td>0.30</td>
<td>0.45</td>
</tr>
<tr>
<td>R²</td>
<td>0.91</td>
<td>0.97</td>
<td>0.93</td>
<td>0.88</td>
</tr>
<tr>
<td>NS</td>
<td>0.82</td>
<td>0.94</td>
<td>0.80</td>
<td>0.64</td>
</tr>
</tbody>
</table>

*Units of bias and RMSE for runoff and water table depth are cm and for P and N loads are kg/ha. The rest of statistics are unitless for all variables.

Table 4-30. Monthly statistics for the verification site S1

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Runoff</th>
<th>Water Table</th>
<th>P Load</th>
<th>N Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>0.46</td>
<td>432.09</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>RE</td>
<td>0.40</td>
<td>-0.27</td>
<td>0.03</td>
<td>0.20</td>
</tr>
<tr>
<td>RMSE</td>
<td>1.48</td>
<td>735.87</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td>CV</td>
<td>1.28</td>
<td>-0.45</td>
<td>0.87</td>
<td>1.81</td>
</tr>
<tr>
<td>R²</td>
<td>0.76</td>
<td>0.88</td>
<td>0.85</td>
<td>0.61</td>
</tr>
<tr>
<td>NS</td>
<td>0.67</td>
<td>0.82</td>
<td>0.85</td>
<td>0.60</td>
</tr>
</tbody>
</table>

*Units of bias and RMSE for runoff and water table depth are cm and for P and N loads are kg/ha. The rest of statistics are unitless for all variables.

Table 4-31. Annual statistics for the verification site S1

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Runoff</th>
<th>Water Table</th>
<th>P Load</th>
<th>N Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td>5.48</td>
<td>5185.17</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>RE</td>
<td>0.40</td>
<td>-0.27</td>
<td>0.03</td>
<td>0.20</td>
</tr>
<tr>
<td>RMSE</td>
<td>6.27</td>
<td>6709.44</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>CV</td>
<td>0.45</td>
<td>-0.34</td>
<td>0.23</td>
<td>0.65</td>
</tr>
<tr>
<td>R²</td>
<td>0.91</td>
<td>0.14</td>
<td>0.94</td>
<td>0.63</td>
</tr>
<tr>
<td>NS</td>
<td>0.61</td>
<td>0.81</td>
<td>0.92</td>
<td>0.58</td>
</tr>
</tbody>
</table>

*Units of bias and RMSE for runoff and water table depth are cm and for P and N loads are kg/ha. The rest of statistics are unitless for all variables.
Figure 4-6. Relative sensitivities of the total surface runoff of 6-year simulation period over the selected input parameters for the pasture sites W6 and S4 (SatK = saturated hydraulic conductivity; ResK = restrictive layer hydraulic conductivity; relative sensitivities are unitless).
Figure 4-7. Relative sensitivities of the maximum water table depth of 6-year simulation period over the selected input parameters for the pasture sites W6 and S4 (SatK = saturated hydraulic conductivity; ResK = restrictive layer hydraulic conductivity; relative sensitivities are unitless).
Figure 4-8. Relative sensitivities of the total P load of 6-year simulation period over the selected input parameters and variables for the pasture sites W6 and S4 (SatK = saturated hydraulic conductivity; ResK = restrictive layer hydraulic conductivity; relative sensitivities are unitless).
Figure 4-9. Relative sensitivities of the total N load of 6-year simulation period over the selected input parameters for the pasture sites W6 and S4 (SatK = saturated hydraulic conductivity; ResK = restrictive layer hydraulic conductivity; relative sensitivities are unitless).
Figure 4-10. Continuous simulation of groundwater table depth from September 2000 through December 2003 for the calibration site W6.

Figure 4-11. Continuous simulation of groundwater table depth from September 2000 through December 2003 for the verification site W7.
Figure 4-12. Continuous simulation of groundwater table depth from September 2000 through December 2003 for the calibration site S4.

Figure 4-13. Continuous simulation of groundwater table depth from September 2000 through December 2003 for the verification site S1.
Figure 4-14. Continuous simulation of surface runoff from July 1998 through December 2003 for the calibration site W6.

Figure 4-15. Continuous simulation of surface runoff from July 1998 through December 2003 for the verification site W7.
Figure 4-16. Continuous simulation of surface runoff from July 1998 through December 2003 for the calibration site S4.

Figure 4-17. Continuous simulation of surface runoff from July 1998 through December 2003 for the verification site S1.
Figure 4-18. Continuous simulation of P loads from July 1998 through December 2003 for the calibration site W6.

Figure 4-19. Continuous simulation of P loads from July 1998 through December 2003 for the verification site W7.
Figure 4-20. Continuous simulation of P loads from July 1998 through December 2003 for the calibration site S4.

Figure 4-21. Continuous simulation of P loads from July 1998 through December 2003 for the verification site S1.
Figure 4-22. Continuous simulation of N loads from July 1998 through December 2003 for the calibration site W6.

Figure 4-23. Continuous simulation of N loads from July 1998 through December 2003 for the verification site W7.
Figure 4-24. Continuous simulation of N loads from July 1998 through December 2003 for the calibration site S4.

Figure 4-25. Continuous simulation of N loads from July 1998 through December 2003 for the verification site S1.
Figure 4-26. Continuous simulation of surface runoff P concentrations from July 1998 through December 2003 for the calibration site W6.

Figure 4-27. Continuous simulation of surface runoff P concentrations from July 1998 through December 2003 for the verification site W7.
Figure 4-28. Continuous simulation of surface runoff N concentrations from July 1998 through December 2003 for the calibration site W6.

Figure 4-29. Continuous simulation of surface runoff N concentrations from July 1998 through December 2003 for the verification site W7.
Figure 4-30. Continuous simulation of surface runoff P concentrations from July 1998 through December 2003 for the calibration site S4.

Figure 4-31. Continuous simulation of surface runoff P concentrations from July 1998 through December 2003 for the calibration site S1.
Figure 4-32. Continuous simulation of surface runoff N concentrations from July 1998 through December 2003 for the verification site S4.

Figure 4-33. Continuous simulation of surface runoff N concentrations from July 1998 through December 2003 for the verification site S1.
Observed vs. Simulated Monthly Runoff for W6

\[ y = 1.028x - 0.0047 \]
\[ R^2 = 0.8104 \]

Observed vs. Simulated Annual Runoff for W6

\[ y = 0.8024x + 4.9308 \]
\[ R^2 = 0.6883 \]

Figure 4-34. Linear plots of monthly and annual surface runoff from 1998 to 2003 for the calibration site W6.
Figure 4-35. Linear plots of monthly and annual surface runoff from 1998 to 2003 for the verification site W7.
Figure 4-36. Linear plots of monthly and annual water table depth from 1998 to 2003 for the calibration site W6.
Figure 4-37. Linear plots of monthly and annual water table depth from 1998 to 2003 for the verification site W7.
Observed vs. Simulated Monthly P Load for W6

\[ y = 0.9572x + 0.0035 \]

\[ R^2 = 0.7656 \]

Observed vs. Simulated Annual P Load for W6

\[ y = 0.8731x + 0.0654 \]

\[ R^2 = 0.8334 \]

Figure 4-38. Linear plots of monthly and annual P load from 1998 to 2003 for the calibration site W6.
Figure 4-39. Linear plots of monthly and annual P load from 1998 to 2003 for the verification site W7.
Figure 4-40. Linear plots of monthly and annual N load from 1998 to 2003 for the calibration site W6.
Figure 4-41. Linear plots of monthly and annual N load from 1998 to 2003 for the verification site W7.
Figure 4-42. Linear plots of monthly and annual surface runoff from 1998 to 2003 for the calibration site S4.
Figure 4-43. Linear plots of monthly and annual surface runoff from 1998 to 2003 for the verification site S1.
Figure 4-44. Linear plots of monthly and annual water table depth from 1998 to 2003 for the calibration site S4.
Figure 4-45. Linear plots of monthly and annual water table depth from 1998 to 2003 for the verification site S1.
Observed vs. Simulated Monthly P Load for S4

\[ y = 0.9657x + 0.0229 \]
\[ R^2 = 0.85 \]

Observed vs. Simulated Annual P Load for S4

\[ y = 1.0312x + 0.2074 \]
\[ R^2 = 0.9311 \]

Figure 4-46. Linear plots of monthly and annual P load from 1998 to 2003 for the calibration site S4.
Figure 4-47. Linear plots of monthly and annual P load from 1998 to 2003 for the verification site S1.
Figure 4-48. Linear plots of monthly and annual N load from 1998 to 2003 for the calibration site S4.
Figure 4-49. Linear plots of monthly and annual N load from 1998 to 2003 for the verification site S1.
Figure 4-50. Duration curves of daily surface runoff and water table depth for the calibration site W6.
Figure 4-51. Duration curves of daily P and N loads for the calibration site W6.
Figure 4-52. Duration curves of daily surface runoff and water table depth for the verification site W7.
Figure 4-53. Duration curves of daily P and N loads for the verification site W7.
Figure 4-54. Duration curves of daily surface runoff and water table depth from 1998 to 2003 for the calibration site S4.
Figure 4-55. Duration curves of daily N and P loads from 1998 to 2003 for the calibration site S4.
Figure 4-56. Duration curves of daily surface runoff and water table depth from 1998 to 2003 for the verification site S1.
Figure 4-57. Duration curves of daily N and P loads from 1998 to 2003 for the verification site S1.
CHAPTER 5
VEGETATION DYNAMICS SIMULATION MODEL

Introduction

A vegetation dynamics simulation model was developed to predict plant growth in flatwoods watersheds where various landscapes such as wetlands, uplands and transition zones coexist. Best management practices (BMPs) intended to improve water quality in Lake Okeechobee (for example, increased water levels and reduced cattle stocking rates) impact hydrology and nutrient cycling in these watersheds and thus affect vegetation dynamics. Previous studies have indicated that vegetation composition patterns can change over time and space when either hydrology or nutrient dynamics are changed. Some species may expand spatially to encroach the habitats where other species were previously established, while other may decline in their original habitats because of the adverse growth environment caused by these changes. Therefore, the vegetation composition pattern, as an integrated ecohydrologic indicator, may help to identify changes in soil, water, and nutrient conditions in a watershed where BMPs are being implemented if the feedback relationships between vegetation and hydrology and nutrients are well understood. Additionally, well-calibrated numerical vegetation simulation models can be very useful in reducing the cost of field experiments, gaining insights into relevant processes, and predicting long-term trends. Therefore, a vegetation dynamics simulation model was developed in this Chapter to couple with the hydrologic and nutrient models discussed in the previous Chapters.
The available data to establish and calibrate a vegetation model for pasture and wetland plants in south Florida flatwoods watersheds is very limited. Therefore a simple model that avoids overwhelming data requirements, but is still capable of capturing the vegetation dynamics in a logical manner is required. When sufficient data become available in the future, the model can be further improved and calibrated.

Consequently, the objectives of this study are to develop a dynamic vegetation model to simulate

- Daily biomass productivity and leaf area index.
- Plant growth dynamics limited by water and nutrient availabilities.
- Evapotranspiration with consideration of multiple species.
- Nutrient uptake with consideration of multiple species.
- Species composition pattern over time and space as impacted by water and nutrient availability.

A vegetation model, built on a spatially heterogeneous landscape through a land segment system in which the number, size and shape of the land segments can be defined according to land cover, soil and vegetation types, and topography, was developed. Each land segment is initialized with one or multiple species, which compete for light, water and nutrients. For each time step, plant growth is simulated, driven by climate variables including solar radiation and temperature. The growth reduction caused by suboptimal water and nutrient availability is calculated daily and applied to reduce the potential plant growth. Losses in plant biomass due to fire, harvest, and senescence are withdrawn from the biomass pool and affect plant growth and competition in the next time step. Within a land segment, homogeneity of plant distribution, plant biomass, leaf area, and soil conditions is assumed. The population dynamics of the herbivores and their grazing
impacts to plant growth are not included in this study, but these impacts can be incorporated into the model once an herbivore movement model is developed. Land segments are dependent on each other in the sense that water and nutrient flows are transferred between land segments, and there are feedback relationships between the water, nutrient and vegetation models. Therefore, the vegetation development within one land segment indirectly affects the vegetation development in another land segment.

The main processes described in this model are light interception, dry matter production and partitioning, and leaf area development. The driving variables of the model are climate data (radiation and temperature) and the time step is daily. The state variables are aboveground and belowground biomass and their corresponding N and P pools. Water stress reflecting water limitation, water logging reflecting anoxic soil water conditions, and nitrogen (N) and phosphorus (P) stress reflecting nutrient deficiencies are calculated on a daily basis in the model, and their combination defines a growth reduction factor affecting the plant growth.

The following assumptions were made in the development of the vegetation model:

- Light interception occurs in one canopy layer that contains all plant species of interest.
- Potential plant growth is driven primarily by solar radiation and temperature, but it is reduced by the water and nutrient limitations.
- Within land segments, functional groups of species are simulated instead of individual plants. Thus all plants within a species are treated as a single entity.
- Total dry matter for each species is simply partitioned into aboveground and belowground biomass.
- All species within land segments are assumed to have the same root lengths and have the same distribution fraction of roots in the computational soil layers.
- Alive plant N and P concentrations are uniform throughout the entire plant.
Plant senescence starts when the sum of leaf area index (LAI) over all species is greater than the critical LAI.

When long-term inundation causes the death of plants, 25% of the aboveground and belowground biomass and the corresponding N and P are removed per day from live biomass pools to dead biomass pools.

When fire occurs, 95% of the aboveground biomass and the corresponding N and P in the aboveground biomass are removed for all species in the land segment.

Methodology

Model Structure

The model for simulating the biomass productivity of pasture and wetland grasses in order to understand how spatial biomass distribution and composition pattern are impacted by altered hydrology and nutrient concentrations is depicted in Figure 5-1. This model is designed based on the previous studies by Spitters and Schapendonk (1990), Ivens (1992), Kooman (1995), Jones and Luyten (1998), Van Oene et al. (1999), and Jones et al. (2000).

The basic processes in this model are light interception, conversion of light into dry matter production, and allocation of dry matter between aboveground and belowground dry matter. The impacts from the changes in hydrology and nutrient concentrations are expressed in growth limiting factors. Water stress or logging indicate water deficiency or water logged soil conditions, and N and P stress factors indicate N and P deficiency. These stress factors are combined to define a growth reduction factor that is used in the model to reflect the adverse growth conditions causing the reduction of the potential dry matter production. Different species have different growth niches (Whittaker and Levin, 1975) defined by the plant’s physiological and phenological characteristics, which determine whether a species can adapt to the changing environment. The resulting plant
composition pattern responding to the new environment can be different and can thus be an indicator of how and to what extent the ecology of a watershed is impacted.

Figure 5-1. Diagram for daily plant growth in relation to weather and water and nutrient availabilities (DM = dry matter; N = nitrogen; P = phosphorus; and SLA = specific leaf area).

**Plant Growth**

**Potential growth**

If a plant is free from weed competition, pests and disease, and well-supplied with water and nutrients, the growth rate is determined by incident light, ambient temperature and plant characteristics. This growth rate is described as the potential growth rate (Ivens, 1992). In the model developed here, the potential growth rate ($\Delta W_{pot,i,t}$ [kg/m$^2$/day]) for each species $i$ on day $t$ is calculated through a linear function of the
absorbed light and a mean radiation-use efficiency parameter (Cannell et al., 1987; Spitters and Schapendonk, 1990) as shown in Equation (5-1). This function is modified by a temperature factor (Van Oene et al., 1999).

\[
\Delta W_{pot,i,t} = RUE_i \times I_{abs,i,t} \times F_{i,t}(T_t) \tag{5-1}
\]

where \(RUE_i\) is the average radiation use efficiency of species \(i\) [kg/MJ(PAR)] and is a summary variable for all processes dealing with photosynthesis and respiration. \(I_{abs,i,t}\) is the light interception by species \(i\) on day \(t\), which is calculated using the Lambert-Beer equation (Monsi and Saeki, 1953). Each species absorbs an amount of light proportional to its share in the total weighted leaf area multiplied by the species specific extinction coefficient times the total light absorption of the vegetation as shown in Equation (5-2):

\[
I_{abs,i,t} = \frac{k_{ext,i} \times LAI_{i,t-1} \times I_{0,t} \times (1 - e^{-\sum k_{ext,i} \times LAI_{i,t-1}})}{\sum_i k_{ext,i} \times LAI_{i,t-1}} \tag{5-2}
\]

where \(I_{abs,i,t}\) is the absorbed radiation by species \(i\) [MJ(PAR)/m\(^2\)/day]; \(k_{ext,i}\) is the light extinction coefficient of species \(i\) [-]; \(LAI_{i,t-1}\) is the leaf area index of species \(i\) [m\(^2\) leaf /m\(^2\) ground] on day \(t-1\); \(I_{0,t}\) is the incoming photosynthetic active radiation (PAR) on day \(t\) [MJ/ m\(^2\)/day]. For simplicity, the difference in light interception at various positions in the canopy is neglected; instead it is assumed only one canopy layer exists, which contains all plant species. The distribution of the plant species over this layer is determined by the leaf biomass distribution of the species. Leaf area per species is calculated from biomass and specific leaf area (SLA\(_i\)) (see Equation (5-12)).
Figure 5-2. Diagram of temperature function for species i.

\[ F_{i,t}(T_t) \text{-[-]} = \begin{cases} 
0 & T_t \leq T_{\text{min},i} \text{ or } T_t \geq T_{\text{max},i} \\
\frac{\left( T_t - T_{\text{min},i} \right)}{\left( T_{\text{opt},1,i} - T_{\text{min},i} \right)} & T_{\text{min},i} < T_t < T_{\text{opt},1,i} \\
1 & T_{\text{opt},1,i} \leq T_t \leq T_{\text{opt},2,i} \\
\frac{\left( T_{\text{max},i} - T_t \right)}{\left( T_{\text{max},i} - T_{\text{opt},2,i} \right)} & T_{\text{opt},2,i} < T_t < T_{\text{max},i}
\end{cases} \]  

\text{in which, } T_t \text{ is the mean air temperature on day } t \text{ [°C], obtained by taking the average of daily maximum and minimum air temperatures, which are inputs to the model; } T_{\text{min},i} \text{ is the base/minimum temperature for assimilation for species } i \text{ [°C]; } T_{\text{opt},1,i} \text{ is the optimum temperature 1 for assimilation for species } i \text{ [°C]; } T_{\text{opt},2,i} \text{ is the optimum temperature 2 for assimilation for species } i \text{ [°C]; } T_{\text{max},i} \text{ is the maximum temperature for assimilation for species } i \text{ [°C]. An example diagram showing the relationship between the temperature function and daily air temperature is shown in Figure 5-2. For this model, only one temperature function is assumed for each species throughout the entire growing season.}
Reduced growth

The plant growth rate may be limited by N or P deficiency, water shortage or water logging during different parts of the growing season:

\[ \Delta W_{\text{red},i,t} = \Delta W_{\text{pot},i,t} \times RF_{i,t} \]  (5-4)

\[ \Delta N_{i,t} = \Delta W_{\text{pot},i,t} \times RF_{i,t} \times CN_{i,t} \]  (5-5)

\[ \Delta P_{i,t} = \Delta W_{\text{pot},i,t} \times RF_{i,t} \times CP_{i,t} \]  (5-6)

where \( \Delta W_{\text{red},i,t} \) is the reduced dry matter production rate of species i [kg/m²/day]; \( \Delta N_{i,t} \) and \( \Delta P_{i,t} \) are the N and P uptake rates corresponding to \( \Delta W_{\text{red},i,t} \) [kg/ha], respectively; \( RF_{i,t} \) is a growth reduction factor [-] of species i, which integrates the limiting factors from water (see details in the following growth reduction factor section), N and P; and \( CN_{i,t} \) and \( CP_{i,t} \) are the biomass N and P percents, respectively (see Equations (5-31) and (5-38)) [%].

Applying the Euler’s method to Equations (5-4) to (5-6), the total dry matter production and dry matter N and P can be calculated as

\[ W_{\text{red},i,t} = W_{\text{red},i,t-1} + RUE_i \times I_{\text{abs},i,t} \times F_{i,t}(T_{i}) \times RF_{i,t} \times \Delta t \]  (5-7)

\[ N_{i,t} = N_{i,t-1} + RUE_i \times I_{\text{abs},i,t} \times F_{i,t}(T_{i}) \times RF_{i,t} \times CN_{i,t} \times \Delta t \]  (5-8)

\[ P_{i,t} = P_{i,t-1} + RUE_i \times I_{\text{abs},i,t} \times F_{i,t}(T_{i}) \times RF_{i,t} \times CP_{i,t} \times \Delta t \]  (5-9)

where \( W_{\text{red},i,t} \) and \( W_{\text{red},i,t-1} \) are the dry matter production on day t and t-1, respectively [kg/m²]; \( N_{i,t} \) and \( N_{i,t-1} \) are the total dry matter N on day t and t-1 [kg/ha]; \( P_{i,t} \) and \( P_{i,t-1} \) are the total biomass P on day t and t-1 [kg/ha], respectively; and \( \Delta t \) is the time step, which is one day in this model.
Dry matter partitioning

The total dry matter production is distributed among various plant organs. A first partitioning is that between aboveground and belowground plant organs, characterized by the shoot/root ratio, $f_{a,i}$, which is generally a function of growth stage, but in this model is assumed to be a constant value. Dry matter may be further partitioned into economic products (e.g. grain, fruits) and crop residue (e.g. straw, stubble). However, for this model, the total dry matter is only partitioned into the aboveground and belowground dry matter using the equations:

$$W_{a,i,t} = W_{red,i,t} \times (1 - f_{a,i}) \quad (5-10)$$

$$W_{b,i,t} = W_{red,i,t} \times f_{a,i} \quad (5-11)$$

where $W_{a,i,t}$ is the aboveground dry matter at the time step of $t$ [kg/m$^2$]; $W_{b,i,t}$ is the belowground dry matter at the time step of $t$ [kg/m$^2$]; $f_{a,i}$ is the dry matter partitioning coefficient [-].

Leaf Area Index

Changes in the leaf area index ($LAI_{i,t}$) for each species on day $t$ may be caused by grazing, fire, and harvesting in addition to plant growth and senescence. Equation (5-12) shows the accumulated daily leaf area can be calculated by multiplying the aboveground biomass by the specific leaf area on the same day.

$$LAI_{i,t} = W_{a,i,t} \times SLA_i \quad (LAI_{min,i} \leq LAI_{i,t} \leq LAI_{max,i}) \quad (5-12)$$

where $LAI_{i,t}$ is the leaf area index for each species $i$ at the time step of $t$ [m$^2$ leaf/m$^2$ ground]; $W_{a,i,t}$ is the daily aboveground dry matter [kg DM/m$^2$ ground] for species $i$ at the time step of $t$; $SLA_i$ is the specific leaf area to convert the leaf dry matter into leaf area index [m$^2$ leaf/kg DM leaf]. However, the calculated $LAI_{i,t}$ should not exceed a pre-
defined maximum LAI_{max,i} to represent the steady state a mature species stand reaches associated with the long-term climate, nor should it fall below a pre-specified minimum LAI_{min,i} to account for the leaf area or stubble that is inaccessible to cattle due to their bite structure (Kiker, 1998). When long-term water inundation causes the death of a species, discussed in the following section, a threshold LAI value of 0.001 was assumed in the model to allow regrowth once the soil conditions become favorable.

**Plant Senescence**

Plant senescence is assumed to start when the daily sum of leaf areas

\[
(LAI_{sum} = \sum_{i} LAI_{i,t} [m^2 \text{ leaf/m}^2 \text{ ground}])
\]

of all species on one land segment exceeds the critical leaf area (LAI_{cr} [m^2 \text{ leaf/m}^2 \text{ ground}]), an input to the model. This approach accounts for senescence associated with insufficient light availability to maintain all of the biomass that has accumulated and is now shaded. All species are assumed to be affected in the same way, i.e., when LAI_{sum} exceeds this critical value, each species senesces LAI, biomass, N and P in proportion to its leaf areas. This process leads to a reduction in both aboveground and belowground biomass and corresponding N and P for all species on that land segment for each day when LAI_{sum} exceeds LAI_{cr}. The daily total senesced biomass \(W_{s,i,t} [\text{kg/ha}]\) and the corresponding N \(N_{s,i,t} [\text{kg/ha}]\) and P \(P_{s,i,t} [\text{kg/ha}]\) removed through the senesced biomass for each species on that land segment can be calculated (Jones JW, personal communication, 2006):

\[
W_{s,i,t} = \text{Frac}_{bs} \times \left( \frac{LAI_{sum} - LAI_{cr}}{LAI_{cr}} \right) / SLA_i \tag{5-13}
\]

\[
N_{s,i,t} = N_{i,t} \times \frac{W_{s,i,t}}{W_{red,i,t}} \tag{5-14}
\]

\[
P_{s,i,t} = P_{i,t} \times \frac{W_{s,i,t}}{W_{red,i,t}} \tag{5-15}
\]
where Fracbs is the fraction of biomass above the critical level to senesce per day [-], which is assumed to be a constant value in the model for all species. The senesced biomass and biomass N and P decrease the amount of live biomass and its corresponding N and P pools:

\[ W_{\text{red},i,t} = W_{\text{red},i,t} - W_{s,i,t} \]  
\[ N_{i,t} = N_{i,t} - N_{s,i,t} \]  
\[ P_{i,t} = P_{i,t} - P_{s,i,t} \]

Accordingly, plant residue and soil biomass are increased by the senesced biomass and N and P:

\[ M_{r,t} = M_{r,t-1} + W_{s,i,t} \times (1 - f_{a,i}) \]  
\[ M_{s,t} = M_{s,t-1} + W_{s,i,t} \times f_{a,i} \]  
\[ M_{m,t} = M_{m,t-1} + N_{s,i,t} \times (1 - f_a) \]  
\[ M_{sn,t} = M_{sn,t-1} + N_{s,i,t} \times f_a \]  
\[ M_{rp,i,t} = M_{rp,i,t-1} + P_{s,i,t} \times (1 - f_a) \]  
\[ M_{sp,i,t} = M_{sp,i,t-1} + P_{s,i,t} \times f_a \]

where \( M_{r,t} \) and \( M_{r,t-1} \) are the residue biomass on day \( t \) and \( t-1 \) [kg/ha]; \( M_{s,t} \) and \( M_{s,t-1} \) are the soil biomass on day \( t \) and \( t-1 \) [kg/ha]; \( M_{m,t} \) and \( M_{m,t-1} \) are the residue biomass N on day \( t \) and \( t-1 \) [kg/ha]; \( M_{sn,t} \) and \( M_{sn,t-1} \) are the soil biomass N on day \( t \) and \( t-1 \) [kg/ha]; \( M_{rp,t} \) and \( M_{rp,t-1} \) are the residue biomass P on day \( t \) and \( t-1 \) [kg/ha]; \( M_{sp,t} \) and \( M_{sp,t-1} \) are the soil biomass P on day \( t \) and \( t-1 \) [kg/ha].
Evapotranspiration

Evapotranspiration (ET) described in Chapter 3 does not consider the transpiration partitioning among multiple plant species, instead it was designed for one plant species within a land segment. To account for the transpiration by multiple plant species with different crop coefficients, the method for estimating ET in Chapter 3 was modified. The ET process is important in the context of the vegetation simulation in that transpiration is the driving force for nutrient uptake, and insufficient ET leads to reduced plant growth due to water stress discussed in the following section.

In this process, first, a lumped potential evapotranspiration (PET) for all species in a land segment is calculated by multiplying reference evapotranspiration (RET, input or calculated by the model) by a crop coefficient that is weighted by the LAI of each species within one land segment:

\[ \sum \sum (LAI_{i,t-1} \times VICAY_{i,t}) \times \sum LAI_{i,t-1} \]

where \( WV1CAY_t \) is the weighted crop coefficient on day \( t \) [-], which represents all existing plant species in the land segment. \( LAI_{i,t-1} \) is the leaf area of species \( i \) on day \( t-1 \) [m\(^2\) leaf/m\(^2\) ground], and \( VICAY_{i,t} \) is the crop coefficient of species \( i \) [-]. Using the lumped crop coefficient, a partitioning fraction (\( Frac_t \) [-]), with a range of values from 0 to 0.95, can be defined as:

\[
Frac_t = \begin{cases} 
0.95 \frac{(WV1CAY_t - 0.2)}{0.8} & \text{if } WV1CAY_t > 0.2 \\
0 & \text{if } WV1CAY_t \leq 0.2 
\end{cases} 
\]
Thus the potential plant transpiration \( T_{\text{pot},t} \), which is lumped over species and is required later for calculating the water stress factor (see Equation (5-44)), can be obtained:

\[
T_{\text{pot},t} = \text{Frac}_t \times \text{PET}_t
\]  

(5-27)

Next, the lumped PET is applied from the top soil layer downward to the deeper soil layers in the root zone. The layer actual evapotranspiration \( \text{LET}_{j,t} \) is the minimum between the \( \text{PET}_t \) and the available water storage (beyond the wilting point) for a specific soil layer \( j \). If there is still some PET left after applying in the upper soil layer, then the remaining PET will be applied to the next soil layer and so forth until all PET is used up or the bottom soil layer in the root zone is reached. Using the same method in Equation (5-27), the layer \( \text{LET}_{j,t} \) can be split between layer soil water evaporation \( \text{AET}_{S,j,t} \) and layer plant transpiration \( \text{AET}_{T,j,t} \), the latter is required for later use in estimating nutrient uptake.

\[
\text{AET}_{T,j,t} = \text{LET}_{j,t} \times \text{Frac}_t
\]  

(5-28)

\[
\text{AET}_{S,j,t} = 1 - \text{AET}_{T,j,t}
\]  

(5-29)

Furthermore, the layer actual transpiration can be split among species existing in one land segment using the leaf area ratios (Jones JW, private communication, 2006):

\[
T_{i,j,t} = \text{AET}_{T,j,t} \times \frac{1 - e^{-k_{sw,j} \times \text{LAI}_{i,t}}}{\sum_i (1 - e^{-k_{sw,j} \times \text{LAI}_{i,t}})}
\]  

(5-30)

where \( T_{i,j,t} \) is the species-specific transpiration [mm] and the index \( j \) indicates the number of soil layer.

**Nitrogen Uptake**

N uptake in GLEAMS (Knisel and David, 1999) was patterned after that in the EPIC model (Sharpley and Williams, 1990) for estimation of nitrogen demand, but it was
modified to consider the difference in nitrate and ammonium uptake by plants. All vegetation species differ in their affinity for nitrate or ammonia, but in the GLEAMS model nitrate and ammonia uptake are treated equally in those soil layers where transpiration occurs. In the vegetation model developed, the N uptake approach in GLEAMS was modified to account for the N uptake by multiple plant species in one land segment.

![Graph](image)

Figure 5-3. An example relationship between plant biomass nitrogen concentration and growth ratio (using empirical coefficients $C_1 = 1.25$ and $C_2 = -0.278$ in Fraisse and Campbell (1997). LAI was assumed to range from 0.01 to 5.2).

In the N uptake process, the nitrogen concentration, $C_{N_{i,t}}$, of the plant biomass for species $i$ on day $t$ [%], is calculated using the equation:

$$C_{N_{i,t}} = C_{1i} \times GRT_{i,t}^{C_{2i}}$$  \hspace{1cm} (5-31)

where $C_{1i}$ and $C_{2i}$ are constant empirical input coefficients [-] and $GRT_{i,t}$ is the growth ratio [-], which is defined as:

$$GRT_{i,t} = \frac{LAI_{i,t}}{POTLAI_i}$$  \hspace{1cm} (5-32)

where $LAI_{i,t}$ is the leaf area [m$^2$ leaf/m$^2$ ground] for species at time $t$, and $POTLAI_i$ is the potential leaf area [m$^2$ leaf/m$^2$ ground] for species $i$, which represents the maximum leaf
area without the constraints of water and nutrient limitations over the growing season.

The relationship between the plant nitrogen concentration and growth ratio can be illustrated through the example diagram as seen in Figure 5-3.

Using Equation (5-33) the total dry matter N, TDMN_{i,t}, of species i at time t [kg/ha] can be estimated:

$$ TDMN_{i,t} = CN_{i,t} \times W_{red,i,t} $$ \hspace{1cm} (5-33)

where $W_{red,i,t}$ is the total biomass of species i estimated in Equation (5-7). The daily N demand, DEMN_{i,t} [kg/ha], for species i at time step t is then calculated as the difference between the dry matter N at two successive time steps, which represents the optimum N required to maintain plant growth without N limitation.

$$ DEMN_{i,t} = TDMN_{i,t} - TDMN_{i,t-1} $$ \hspace{1cm} (5-34)

The N supply, determined by the N availability in soils, can be calculated by multiplying the N concentration with transpiration from the respective layers. In the model, N uptake is treated equally for both nitrate and ammonia. The amount of N taken up by species i from each soil layer j where transpiration occurs, including nitrate uptake (UPNH_{i,j,t} [kg/ha]) and ammonia uptake (UPNO_{i,j,t} [kg/ha]) can be calculated:

$$ UPNO_{i,j,t} = CNO3W_{s,d,j} \times T_{i,j,t} $$ \hspace{1cm} (5-35)

$$ UPNH_{i,j,t} = CNH4W_{s,d,j} \times T_{i,j,t} $$ \hspace{1cm} (5-36)

where $CNO3W_{s,d,j}$ and $CNH4W_{s,d,j}$ are the nitrate and ammonium concentration for the jth soil layer, respectively, determined from Equations (4-2) and (4-9) described in Chapter 4, and $T_{i,j,t}$ is the transpiration that occurred from that soil layer for species i at time t determined from Equation (5-25). The total uptake of N is summed for each plant
species over the number of soil layers where transpiration occurs and it increases the alive biomass N pool by

\[ N_{up,t} = \sum_i \sum_j U_{PNO_{i,j,t}} + \sum_i \sum_j U_{PNH_{i,j,t}} \]  

(5-37)

where \( N_{up,t} \) is the total N uptake per day [kg/ha].

The N demand can be greater or less than the N supply. If demand is less than supply, then the uptake occurs in the amount calculated in Equations (5-35) and (5-36). Otherwise, a demand factor, the ratio between the demand and availability, is calculated to reduce the uptake to the demand for both nitrate and ammonia at soil layers where transpiration occurs.

![Graph](image)

Figure 5-4. An example relationship between plant biomass phosphorous concentration and growth ratio (using empirical coefficients \( C1 = 1.25 \) and \( C2 = -0.278 \) in Fraisse and Campbell (1997). LAI was assumed to range from 0.01 to 5.2).

**Phosphorus Uptake**

The algorithm for P uptake is similar to that for N uptake. The optimum P content of the plant biomass [%] is estimated from the nitrogen content (\( C_{N_{i,t}} \) in Equation (5-31)) and the N:P ratio, \( N_{PR_i} [-] \), an input to the model, as:

\[ CP_{i,t} = \frac{C_{N_{i,t}}}{N_{PR_i}} \]  

(5-38)
Figure 5-4 shows an example relationship between the plant P concentration and the growth ratio.

The total dry matter P, TDMP_{i,t} [kg/ha] for species i at time t, is calculated using the equation

$$TDMP_{i,t} = CP_{i,t} \times W_{red,i,t}$$  \hspace{1cm} (5-39)

and the P demand for species i at time t, DEMP_{i,t} [kg/ha], is determined by the difference between the dry matter P on two successive days as

$$DEMP_{i,t} = TDMP_{i,t} - TDMP_{i,t-1}$$  \hspace{1cm} (5-40)

Uptake of labile P, UPLP_{i,t} [kg/ha], is estimated for each layer where transpiration, AE_{T,t}, occurs using

$$UPLP_{i,j,t} = CPLAB_{s,d,t} \times T_{i,j,t}$$  \hspace{1cm} (5-41)

where the concentration of labile P, CPLAB_{s,d,t}, is determined by Equation (4-15) in Chapter 4. The total uptake of P is the sum over all species i and all layers j where transpiration occurs. The P taken up is converted into the plant biomass P:

$$P_{up,t} = \sum_i \sum_j UPLP_{i,j,t}$$  \hspace{1cm} (5-42)

where $P_{up,t}$ is the plant biomass P [kg/ha], which will be used to calculate plant P concentration for determining the P stress in the following section. Similar to N, a demand factor for P that is a ratio between the demand and availability of P is calculated to reduce the uptake of P when supply exceeds demand.

**Growth Reduction Factor**

The growth reduction factor, RF_{i,t}, used in Equation (5-5) is a unitless, species-specific growth reduction factor with a value ranging from 0 to 1, which is obtained by
taking the minimum value of water stress, water logging, and N and P stress factors as shown in the following equation:

$$RF_{i,t} = \min(F_{WS,i,t}, F_{WL,i,t}, F_{N,i,t}, F_{P,i,t})$$ (5-43)

where $F_{WS,i,t}$ is the water stress factor for species $i$ [-]; $F_{WL,i,t}$ is the water logging factor for species $i$ [-]; $F_{N,i,t}$ is the N stress factor [-]; and $F_{P,i,t}$ is the P stress factor [-]. The details regarding these factors are discussed below.

**Water stress and logging factors**

Water is one of the limiting growth factors due to its function in transporting nutrients and its assimilation into the plants. The basis for plant production is the uptake of atmospheric carbon dioxide ($CO_2$) for assimilation through the stomata in the epidermis of leaves. As a consequence, water moves in the opposite direction through the stomata, a process referred to as transpiration. If the water supply cannot meet the demand for water, it consequently limits the intake of $CO_2$ and results in the decline of the assimilation rate. In this way, water shortages curtail plant production (Ivens et al., 1992). On the other hand, transpiration can be hampered in soils with moisture content above field capacity, as a result of restricted water/oxygen uptake by the roots. This situation, referred to as water logging (Ivens et al., 1992), is common characteristic of wetland soils.

When soil moisture is above field capacity ($F_c$), soil tends to be saturated and water logging can occur. Under water logging conditions, the growth of most plants is seriously hampered since root respiration, a prerequisite for the uptake of both water and nutrients by the roots, is suppressed due to oxygen shortage. On the other hand, when soil moisture is below the critical soil moisture (SWP) and before it reaches the
permanent wilting point (PWP), moisture extraction is hampered, which leads to drought stress in plants. This causes a reduction in stomatal aperture and hence less water loss and impaired CO\textsubscript{2} assimilation (Ivens, 1992).

Both water stress and logging constrain plant growth. However, different plant species can tolerate water stress or logging to a varying extent and thus these factors are species-specific. Therefore, these two factors are very important in the context of investigating the impact of water retention on ranches. The water stress factor of species \textit{i}, \textit{F\textsubscript{WS,i,t}} can be expressed as a ratio between the actual transpiration and the potential transpiration for species \textit{i}:

$$F_{WS,i,j} = \frac{\sum_{j} AET_{i,j,t}}{T_{pot,t}} \quad (0 \leq F_{WS,i,t} \leq 1)$$

(5-44)

where \textit{AET\textsubscript{i,j,t}} is the layer actual transpiration [mm] for species \textit{i} in layer \textit{j} at time \textit{t}; the index \textit{j} represents the number of soil layers where transpiration occurs; and \textit{T\textsubscript{pot,t}} is the potential transpiration [mm].

When the soil moisture goes above the field capacity, the water logging factor of species \textit{i}, \textit{F\textsubscript{WL,i,t}} [-], can be expressed as

$$F_{WL,i,t} = 0.7 \times \frac{W_{po} - W_{s}}{W_{po} - W_{fc}} + 0.3 \quad (0 \leq F_{WL,i,j} \leq 1)$$

(5-45)

where \textit{W\textsubscript{po}} is the soil porosity [-], \textit{W\textsubscript{s}} is the current soil moisture content [-] at time \textit{t}, and \textit{W\textsubscript{fc}} is the field capacity [-]. For soil layers where transpiration occurs, these soil parameters may be different. To account for these differences, their weighted values by the root fraction are used in Equation (5-45) to calculate the water logging factor.
Duration of inundation is another important factor considered in this model because prolonged standing water may eventually kill some plants that cannot tolerate inundation for a long period. To account for the inundation duration factor, the successive days of inundation (it is assumed that surface ponded water has to exceed 2 cm to be considered inundation) are recorded in the model for each species. Before the number of accumulated days of inundation reaches the maximum length of inundation tolerance (species specific input to the model), plants are assumed to grow at a reduced rate defined in Equation (5-45). Once the maximum inundation tolerance is reached, it is assumed 25% of aboveground and belowground biomass dies daily while inundation continues. During this time it is assumed that no growth for this species occurs.

**Nitrogen stress factor**

The N stress, $F_{N,i,t}$, a factor that determines the growth reduction for species i at time t caused by N deficiency, was modeled according to Seligman and Van Keulen (1981), and is dependent on the actual N concentration of the shoot for species i, $C_{N_{\text{shoot}},i,t}$ [g N/g DM], which is calculated by dividing the plant biomass $N_{s,i,t}$ [kg N/ha] by the plant biomass for species i [kg DM/ha]:

$$CN_{\text{shoot},i,t} = \frac{N_{i,t}}{W_{\text{red},i,t}}$$  (5-46)

where $W_{\text{red},i,t}$ is the plant biomass for species i at time t obtained in Equation (5-7); and $N_{i,t}$ is the biomass N for species i at time t, which is obtained from Equation (5-8). If $CN_{\text{shoot},i,t}$ exceeds the critical value $CN_{cr,i}$ [g N/g DM], plant growth is not reduced. Below this N concentration, growth rate decreases linearly with concentration:

$$F_{N,i,t} = \frac{CN_{\text{shoot},i,t} - CN_{\min,i}}{CN_{cr,j} - CN_{\min,j}} \quad (0 \leq F_{N,i,t} \leq 1)$$  (5-47)
where $N_{\text{min},i}$ is the minimum shoot N concentration [g N/g DM] required to maintain the plant growth input to the model by users.

**Phosphorus stress factor**

The P stress, $F_{p,i,t}$, is a factor that determines the growth reduction for species $i$ at time $t$ caused by P deficiency. Similar to the N stress factor, $F_{p,i,t}$ can be calculated as:

$$F_{p,i,t} = \frac{\text{CP}_{\text{shoot},i,t} - \text{CP}_{\text{min},i}}{\text{CP}_{\text{cr},i} - \text{CP}_{\text{min},i}}$$

\[(0 \leq F_{p,i,t} \leq 1) \quad (5-48)\]

where $\text{CP}_{\text{shoot},i,t}$ is the shoot biomass P concentration for species $i$ at time $t$, which can be obtained by dividing the biomass P ($P_{i,t}$ [kg N/ha]) by the aboveground biomass [kg DM/ha]:

$$\text{CP}_{\text{shoot},i,t} = \frac{P_{i,t}}{W_{\text{red},i,t}}$$

\[(5-49)\]

If $\text{CP}_{\text{shoot},i,t}$ exceeds the critical value $\text{CP}_{\text{cr},i}$ [g N/g DM], plant growth is not reduced. Below this P concentration, growth rate decreases linearly with concentration.

**Hypothetical Scenario Model Testing**

**Scenario Description**

Sufficient vegetation data are not currently available from south Florida flatwoods watersheds to quantitatively test the vegetation model. Therefore, a hypothetical test was designed to evaluate the algorithms of the vegetation model, coupled with the hydrologic and nutrient models developed in Chapters 3 and 4 to determine whether the model behaves as expected when the hydrology and nutrient concentrations are manipulated.
Figure 5-5. Aerial photo showing the layout of the improved summer pasture site S4 and location of associated instrumentation. S1 to S6 indicate the individual summer pasture sites and LS1 to LS12 indicate the land segments divided for the site S4. The dotted lines were made to show the boundary between land segments (modified from MAERC, 2004).

A simple scenario was designed based on the summer pasture S4 (see Figure 5-5) at Buck Island Ranch (described in Chapter 4). To simulate the changes in vegetation dynamics, a water retention BMP was assumed to have been applied on this site, i.e. the water level at the pasture drainage outlet (located in the southwest corner as shown in Figure 5-5) was controlled so that discharges did not occur until the water level inside the pasture reached the design water level which was above the pre-BMP discharge level. To realize this scenario in the model, a weir with an elevation of 8.33 m was set up on the boundary between land segment 11 (hereafter LS11), which has a ground surface elevation of 7.98 m, near the outlet and the downstream. Thus after implementation of
the BMP discharges will occur only when the water elevation of the outlet land segment exceeds 8.33 m. Without the application of water retention BMP, discharge would occur when the water elevation reached 7.985 m (maximum depressional storage in depth = 0.5 cm).

Identical hydrologic and nutrient inputs, as described in Chapter 4, were used for running the coupled model to investigate the vegetation dynamics due to the application of the hypothetical BMP for the pasture site S4. Agricultural activities including fertilization, burning, and stocking were not included, so that the impact due to water retention on vegetation dynamics could be analyzed independently. By holding the water levels higher at the outlet, the soil inundation period is prolonged in the pasture and thus the length of anoxic soil conditions is extended as well. This type of hydrologic change may affect nutrient cycling processes that may alter the concentrations of N and P. Changes in both hydrologic regime and nutrient cycling may impact plant growth. Vegetation species that do not adapt well to wet soil conditions for prolonged periods may experience growth reduction and eventually vanish from the site while others that adapt well to such conditions may expand their areas. Over time, the spatial composition patterns of vegetation species may change, and these patterns may be used as an indicator of soil and water conditions. To compare the changes in species composition pattern over time and space, the model was run twice to obtain simulation results before and after holding the water at a higher level (hereafter called pre-BMP and post-BMP, respectively).

Multiple plant species exist in the pasture site S4 as seen in Table 5-1, among which bahiagrass (*Paspalum notatum Flügge*) is the most dominant species accounting
for up to 93% of the land cover, while the remaining species account for about 7% together. However, for this test three perennial species including bahiagrass, floralta (*Hemarthria altissima*), and panicum (*panicum rigidulum*) were assumed to be the major species for the pasture site S4. These vegetation species represent those adapted to soil conditions of uplands, transition zones and wetlands, respectively.

S4 was divided into 12 land segments (see Figure 5-5), as discussed in Chapter 4. Each land segment was assumed to have the same amount of initial total biomass (aboveground + belowground) over all selected species, but different percentages of these species (see Table 5-3). The hypothetical assignment of species and percentage of each species was made up according to the locations of land segments. Land segments with higher topographical elevations, far from wetlands were assumed to be relatively drier in their soil conditions than those located near or in wetlands and thus to contain more upland plant species. With the initial biomass, shoot to root ratio ($f_a$), and specific leaf area (SLA) (see Table 5-2), the model can initialize the aboveground and belowground biomass and green LAI for each species in each land segment.

To run the vegetation model, inputs including the time series inputs (see Table 5-2) such as daily solar radiation, maximum and minimum ambient temperatures and the model parameter values must be provided. Other time series data such as grazing, harvest, burning, and tillage must be specified as well if applicable. The required model parameter values were obtained from the literature if they were available. However, the data for floralta and panicum were especially difficult to find and thus they were assumed to have the same values for some parameters as the bahiagrass. Collecting and setting up these species-specific parameters was one of the challenges encountered during
development of the vegetation model. Table 5-4 lists those variables calculated through
the hydrologic and nutrient models and used in the vegetation model and Table 5-5 lists
major daily output variables from the vegetation model.

**Results and Discussion**

**Water and nutrient responses to water retention BMP**

Figures 5-6 to 5-11 show the comparison of surface runoff, water table depth, and
N and P loads and concentrations predicted by the integrated hydrology, nutrient and
vegetation dynamics simulation model before and after BMP for site S4 for a 6-year
simulation period. It is noted that after holding the water level at 8.33 m at the outlet, no
surface runoff (see Figure 5-6) and hence no N and P loads (see Figures 5-8 and 5-9) are
released downstream throughout the entire simulation period. Figure 5-7 shows that the
ponded water remains above the ground surface for much of the wet season after the
water retention BMP is implemented. A period from approximately September 2000 to
February 2001 was drier than the rest of simulation period, thus during this time the water	
Tables stayed fairly deep even with the water retention BMP. Several periods between the
late spring and early summer in years 1999, 2000 and 2002 were also relatively drier with
long-term water table drawdown (see Figure 5-7). After the BMP, the groundwater table
depths were much shallower than those before BMP except during the driest period
discussed above. Meanwhile, several long periods occurred during which soils became
saturated and the water table remained on the ground surface for approximately 6 months.
This occurred primarily from the middle of summer to the early spring between years
depth during these periods (see Figure 5-7) indicates that the soils experience prolonged
saturation and had standing water on the ground surface. Note that Figure 5-7 was made
using the predicted water tables for LS9 where the observation well was installed and the observations from Figure 5-7 may not apply to the entire pasture site.

The simulated results of P and N concentrations in surface water in Figures 5-10 and 5-11, respectively indicate that both P and N concentrations were dramatically decreased after the water retention BMP. The lower P and N concentrations likely result from changes in biochemical processes due to prolonged anoxic soil conditions both in soils and on surface residue. Overall, it was observed that after the water retention BMP, the hydrologic and nutrient dynamics were significantly changed in pasture site S4. The pasture soils become water logged for prolonged periods and nutrient concentrations become significantly lower.

**Influence of differences in temperature sensitivities among species**

The sensitivity of biomass response to the temperature function was recognized during the development of this vegetation model. To investigate the influence of different temperature functions on the predictions of biomass, three scenarios shown in Table 5-6 were designed. In Scenario 1, an identical temperature function was applied for all three species; in Scenario 2, the temperature function for floralta was different from those for other two species, bahia and panicum, which were assumed to have the same temperature function as specified in Scenario 1. The temperature function for floralta in Scenario 2 was modified by shifting -7 °C from the one used for the other two species, allowing floralta to grow in a lower temperature range from 0 °C to 38 °C. In the last scenario, the temperature functions for bahia and panicum were assumed to be the same as those for them in Scenarios 1 and 2, but the temperature function for floralta was further adjusted to allow this species to grow primarily during winter time, in a narrower
temperature range from 0 °C to 30 °C. In order to investigate the sensitivities of biomass productivity specifically to temperature factors, all these scenario tests were performed without simulating the growth reduction, that is, potential biomass production was compared.

Figure 5-12 shows that the predicted aboveground biomass on LS11 varied dramatically among the three scenarios corresponding to different temperature functions. When the identical temperature function was used for all three species in Scenario 1, the predicted potential biomass had similar trends and patterns throughout the simulation period but was different in magnitude among species due to the difference in their initial conditions. This may imply that in this scenario the three species grow in a relatively stable situation without competition with one another. In Scenario 2, the predicted potential biomass for floralta increased tremendously over time whereas the biomass for bahia and panicum decreased and these species tended to disappear from this land segment. This behavior can be explained through the temperature factors for Scenario 2 shown in Figure 5-13. Compared with bahia and panicum, floralta apparently experienced less growth reduction during the winter time in Scenario 2. Even during the summer time, floralta did not suffer much growth reduction. This situation allows more time for floralta to grow in comparison to the other two species.

In Scenario 3, an opposite response from Scenario 2 occurred for predicted biomass for all species. The temperature factors used for Scenario 3 and shown in Figure 5-13 allow both bahia and panicum to grow faster during the summer time while floralta is in its lowest growth time. The resulting increased biomass for bahia and panicum leads to senescence, which reduces the existing biomass for floralta in the same proportion.
Although floralta grows better in winter time in this scenario, the amount of biomass produced during the winter time did not sufficiently balance the loss due to the senescence during the summer time. Over time the production of floralta decreased and gradually this species vanished from this land segment.

These analyses, based on hypothetical temperature functions, demonstrated that a reasonable, species-specific temperature function is very important for reliable simulation results. Temperature sensitivities of different species are needed in order to correctly simulate the changes in competition of species over time and space and in response to BMPs. Nevertheless, such data are not yet available for these species. Therefore, for the remaining analyses in this study, the same temperature function (see Table 5-6) was assumed for all three species for simplicity.

In addition to sensitivity to temperature, these species may differ in their responses to photoperiod as well. Photoperiod effects were not included in the current method because of lack of information. However, differences in photoperiod sensitivity could also have a big impact on seasonal growth and species compositions (Jones JW, private communication, 2006).

**Species composition dynamics due to water retention BMP**

Figure 5-14 shows relative plant distribution (calculated using the aboveground biomass for each species at the end of each year of the simulation period) over land segments throughout the entire simulation period before and after BMP implementation in the summer pasture S4. The distribution in each land segment is expressed as the percentage of total aboveground biomass (since the belowground biomass follows the same patterns, it is not discussed). Simulation results from the pre-BMP scenario case indicate that the basic composition patterns over land segments are approximately the
same over the entire simulation period, and no species vanished from any land segment
where it was initially assigned. Bahia accounted for the most significant percentage of
biomass over the entire pasture throughout the 6-year simulation period, followed by
panicum, and then floralta. The results before the water retention BMP indicate that pre-
BMP soil conditions were relatively favorable for the coexistence of three species.

After the water retention BMP was applied, the composition patterns of species
over the land segments throughout the simulation period changed. In the first three years,
the difference of biomass distribution among species over land segments was not
significant, and the composition patterns of species were very close to those for the pre-
BMP conditions. Although there was some rainfall variability over the first three years
(as discussed in Chapter 4) this variability was not enough to produce changes in biomass
productivity among these species. However, after year 2001, a dramatic change in the
biomass distribution pattern occurred in the land segments close to the drainage outlet,
including LS5, LS7, LS8, LS9, LS10, LS11, and LS12. Panicum grew significantly
faster in those land segments, and floralta showed a similar trend but with a smaller
magnitude. Meanwhile, the bahia biomass decreased dramatically and almost vanished
from LS12, LS11, LS10, and LS9. Additionally, floralta decreased significantly in LS11
where the drainage outlet is located. Due to the lack of a mechanism for new species to
grow in land segments where they are not originally present, there was no noticeable
change observed in LS6. The distribution pattern in 2001 remained similar in years 2002
and 2003, very likely due to the consecutive wet weather conditions. Overall, changes in
biomass distribution for the last three years under the water retention BMP scenario
demonstrate that the soil conditions became more favorable for the development of
panicum, the wetland species; less favorable for floralta, the transition zone species, and least favorable for baiha, the upland species.

Figure 5-14 provides insight into the relative percentages of plant biomass distribution, but it lacks information on the absolute biomass of each species over land segments on a daily basis. Figures 5-15 and 5-16 show the continuous simulation of aboveground biomass for baiha, floralta, and panicum throughout the 6-year simulation period for the pre- and post-BMP scenarios in three selected land segments (LS8, LS11 and LS12), respectively. As seen in Figure 5-15, the aboveground biomass patterns for all species in these selected land segments are basically similar over time for the pre-BMP scenario, and the magnitude of biomass for each species stayed stable over the simulation period. However, Figure 5-16 shows a significant change occurring late during year 2001 for the post-BMP scenario as observed in Figure 5-14. Bahia biomass was reduced significantly in LS8 around the end of year 2001, but began to grow again in year 2002 and 2003 while panicum and floralta increased their growth in all years. In LS11, baiha died out around the end of 2001, followed by floralta in 2001, while at the same time panicum maintained aggressive growth through the entire simulation period. Since LS11 is the land segment immediately connected to the outlet of pasture, after the water retention BMP, it became the most inundated location in the pasture, which eventually caused the die-off of baiha and floralta. The growth dynamics in LS12 was similar to that in LS8. The difference was that baiha was not able to grow back again. This can be explained by the difference in soil conditions in LS8 and LS12. The latter apparently had longer saturated soil conditions than the former. Comparison of the continuous biomass simulation results for the pre- and post-BMP scenarios further
support the conclusion that the application of the water retention BMP caused significant changes in vegetation dynamics.

Figures 5-19 and 5-20 show the growth limiting factors for bahia in LS11 for the pre- and post-BMP scenarios. Consistently, in both scenarios, water stress and water logging were more influential factors than the N and P stress factors. This is reasonable for a pasture site like S4 that has a high background nutrient concentration. The comparison of water stress and logging factors for pre- and post-BMP scenarios indicates that the frequency of water stress was decreased significantly, while that for water logging was increased, after the water retention BMP. This result demonstrates that the model is capable of capturing water dynamics due to the water retention BMP.

**Concluding Remarks**

To simulate vegetation dynamics caused by changes in hydrologic and nutrient dynamics in south Florida flatwoods watersheds, a vegetation model was developed and coupled with the hydrologic and nutrient models developed earlier. In this model, plant biomass production is mainly driven by climate (solar radiation and temperature) and affected by growth reduction factors, including water stress, water logging, and N and P stresses. Total production is simply partitioned between aboveground and belowground biomass and the leaf area is obtained by multiplying the aboveground biomass by the specific leaf area. Three perennial plant species, bahia, floralta, and panicum, were selected as representative of plants adapted to upland, transition zone and wetlands growth conditions, respectively. An analysis of the influence of difference temperature sensitivities among species indicate that reasonable, species-specific temperature functions are needed to correctly simulate the plant competition over time and specie and simulate response to BMPs.
A hypothetical BMP scenario based on the summer pasture site S4 at Buck Island Ranch, Lake Okeechobee Basin, Florida was developed to take advantage of the calibrated hydrologic and nutrient parameters computed in Chapter 4. In this scenario, it is assumed that a water retention BMP that retained all water below an elevation of 8.33 m was implemented in pasture S4. Due to water retention, the soil in the pasture was inundated much longer than when the water was allowed to flow freely off the pasture. The changes in hydrology and hence in nutrient dynamics were demonstrated to have the potential to change vegetation.

The hypothetical scenario test showed that after implementing the water retention BMP, all surface runoff and nutrients were retained inside the pasture site and the periods of water logging or inundation increased. With these changes in hydrology and nutrients, wetland species like panicum survived better than bahia and floralta, while the transition zone species floralta did better than upland species bahia. The spatial distribution patterns of biomass were distinct over time for the pre- and post-BMP scenarios and significant dynamics in the magnitude of biomass and the number of species were observed through the predicted results. Consequently, it was concluded that this vegetation model is capable of simulating vegetation dynamics caused by changes in hydrology and nutrient cycling due to water retention BMPs.

However, the model input parameters, mostly assumed or taken from the literature, may not be sufficient to accurately represent physiological and phenological characteristics of the selected species. Furthermore, the model performance was evaluated in a hypothetical scenario, not against actual field data. In order to use this model for prediction, future efforts in collecting vegetation data and evaluating the model
with observed data and experimentally-derived parameters should be undertaken. In addition, the model needs to be further developed to enable simulation of root length and root biomass distribution to more accurately capture the nutrient uptake and evapotranspiration differences among species, and an algorithm for simulating plant height should be added to enable the feedback relationship between surface runoff and a dynamic surface roughness, which is a function of vegetative cover. A start-up mechanism for new species initiation in land segments should be added to more accurately simulate plant competition and spatial evolution. Finally, an herbivore movement model should be developed to simulate the impacts of cattle behavior and grazing performance on vegetation growth.
### Table 5-1. Percent cover of vegetation on summer pastures S4 (MAERC, 2004).

<table>
<thead>
<tr>
<th>Scientific Name</th>
<th>Common Name</th>
<th>S4</th>
<th>Scientific Name</th>
<th>Common Name</th>
<th>S4</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Paspalum notatum</em></td>
<td>bahiagrass</td>
<td>93%</td>
<td><em>Paspalum urvillei</em></td>
<td>vasey grass</td>
<td>1%</td>
</tr>
<tr>
<td><em>Axonopus affinis</em></td>
<td>carpet grass</td>
<td>1%</td>
<td><em>Juncus effuses</em></td>
<td>softrush</td>
<td>2%</td>
</tr>
<tr>
<td><em>Cynodon dactylon</em></td>
<td>bermuda grass</td>
<td></td>
<td><em>Cyperaceae spp.</em></td>
<td>sedges</td>
<td>1%</td>
</tr>
<tr>
<td><em>Setaria geniculata</em></td>
<td>Foxtail</td>
<td></td>
<td><em>Eupatorium apillifolium</em></td>
<td>dog fennel</td>
<td></td>
</tr>
<tr>
<td><em>Paspalum dilatatum</em></td>
<td>dallis grass</td>
<td></td>
<td><em>Phyla nodiflora</em></td>
<td>Lippia</td>
<td></td>
</tr>
<tr>
<td><em>Centella asiatica</em></td>
<td>Centella</td>
<td>1%</td>
<td><em>Hydrocotyle umbellata</em></td>
<td>pennywort</td>
<td></td>
</tr>
<tr>
<td><em>Sporobolus indicus</em></td>
<td>smut grass</td>
<td></td>
<td><em>Polygonum sp.</em></td>
<td>smartweed</td>
<td>&lt;1%</td>
</tr>
<tr>
<td><em>Andropogon glomeratus</em></td>
<td>Bluestem</td>
<td>1%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 5-2. Parameter values for the different plant species for the vegetation model.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
<th>bahia</th>
<th>floralta</th>
<th>panicum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_0$</td>
<td>Incoming photosynthetic active radiation</td>
<td>MJ/m²/day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>Daily Minimum ambient temperature</td>
<td>°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{\text{max}}$</td>
<td>Daily Maximum ambient temperature</td>
<td>°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{LAI}_{\text{min}}$</td>
<td>Minimum green LAI</td>
<td>m² leaf/m² land</td>
<td>0.10c</td>
<td>0.10c</td>
<td>0.10c</td>
</tr>
<tr>
<td>$\text{LAI}_{\text{max}}$</td>
<td>Potential green LAI</td>
<td>m² leaf/m² land</td>
<td>8.0c</td>
<td>8.0c</td>
<td>8.0c</td>
</tr>
<tr>
<td>$\text{LAI}_{\text{cr}}$</td>
<td>Critical LAI</td>
<td>m² leaf/m² land</td>
<td>5.0c</td>
<td>5.0c</td>
<td>5.0c</td>
</tr>
<tr>
<td>$f_a$</td>
<td>Dry matter partitioning coefficient</td>
<td>–</td>
<td>0.33c</td>
<td>0.33c</td>
<td>0.33c</td>
</tr>
<tr>
<td>$k$</td>
<td>Light extinction coefficient of species</td>
<td>–</td>
<td>0.5d</td>
<td>0.5d</td>
<td>0.5d</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>Base temperature for growth</td>
<td>°C</td>
<td>7g</td>
<td>7g</td>
<td>7g</td>
</tr>
<tr>
<td>$T_{\text{opt1}}$</td>
<td>Optimum temperature 1 below which light interception increases</td>
<td>°C</td>
<td>28g</td>
<td>28g</td>
<td>28g</td>
</tr>
<tr>
<td>$T_{\text{opt2}}$</td>
<td>Optimum temperature 2 above which light interception decreases</td>
<td>°C</td>
<td>35g</td>
<td>35g</td>
<td>35g</td>
</tr>
<tr>
<td>$T_{\text{opt}}$</td>
<td>Base temperature for growth</td>
<td>°C</td>
<td>45g</td>
<td>45g</td>
<td>45g</td>
</tr>
<tr>
<td>$\text{RUE}$</td>
<td>Radiation use efficiency</td>
<td>g MJ/PAR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{SLA}$</td>
<td>Specific leaf area</td>
<td>cm² leaf/g leaf</td>
<td>64.8b</td>
<td>64.8b</td>
<td>64.8b</td>
</tr>
<tr>
<td>$\text{L}$</td>
<td>Maximum water logging limit</td>
<td>day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_1$</td>
<td>Plant NC1</td>
<td>–</td>
<td>1.25c</td>
<td>1.25c</td>
<td>1.25c</td>
</tr>
<tr>
<td>$C_2$</td>
<td>Plant NC2</td>
<td>–</td>
<td>-0.278e</td>
<td>-0.278e</td>
<td>-0.278e</td>
</tr>
<tr>
<td>$C:N$</td>
<td>Carbon: nitrogen ratio</td>
<td>–</td>
<td>80e</td>
<td>80e</td>
<td>80e</td>
</tr>
<tr>
<td>$N:P$</td>
<td>Nitrogen Phosphorus ratio</td>
<td>–</td>
<td>6.7e</td>
<td>6.7e</td>
<td>6.7e</td>
</tr>
<tr>
<td>$\text{CN}_{\text{min}}$</td>
<td>Shoot minimum N concentration</td>
<td>g N/g DM</td>
<td>0.005f</td>
<td>0.005f</td>
<td>0.005f</td>
</tr>
<tr>
<td>$\text{CN}_{\text{cr}}$</td>
<td>Shoot critical N concentration</td>
<td>g N/g DM</td>
<td>0.0135c</td>
<td>0.0135c</td>
<td>0.0135c</td>
</tr>
<tr>
<td>$\text{CP}_{\text{min}}$</td>
<td>Shoot minimum P concentration</td>
<td>g N/g DM</td>
<td>0.005d</td>
<td>0.005d</td>
<td>0.005d</td>
</tr>
<tr>
<td>$\text{CP}_{\text{cr}}$</td>
<td>Shoot critical P concentration</td>
<td>g N/g DM</td>
<td>0.0135d</td>
<td>0.0135d</td>
<td>0.0135d</td>
</tr>
<tr>
<td>$f_{\text{hs}}$</td>
<td>Declining rate due to plant senescence</td>
<td>–</td>
<td>0.0714c</td>
<td>0.0714c</td>
<td>0.714c</td>
</tr>
</tbody>
</table>

*aMeasured through Buck Island project (MAERC, 2004); bFor bahiagrass by Stuart (2004); cAssumed parameter values; dParameter values for *Agrostis stolonifera*, *Phragmites australis*, and *Salix alba* by Van Oene et al.(1998); eParameter values for bahiagrass by Fraisse and Campbell (1997); fParameters values for *Holcus*, *Anthoxanthum*, and *Festuca* by Schippers and Kropff (2001); gTemperature function curve for the vegetative phase by Jones et al. (2000).
Table 5-3. Initial composition percentage and amount for species in each land segment.

<table>
<thead>
<tr>
<th>Land segment</th>
<th>Composition in percentage [%]</th>
<th>Composition in biomass [kg/ha]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bahia</td>
<td>Floralta</td>
</tr>
<tr>
<td>LS1</td>
<td>100</td>
<td>−</td>
</tr>
<tr>
<td>LS2</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>LS3</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>LS4</td>
<td>85</td>
<td>10</td>
</tr>
<tr>
<td>LS5</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>LS6</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>LS7</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>LS8</td>
<td>70</td>
<td>20</td>
</tr>
<tr>
<td>LS9</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>LS10</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>LS11</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>LS12</td>
<td>70</td>
<td>20</td>
</tr>
</tbody>
</table>

*Species does not exist in this land segment.

Table 5-4. Variables calculated from other models.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNH4W</td>
<td>Soil layer nitrate concentration</td>
<td>mg/l</td>
<td>Calculated</td>
</tr>
<tr>
<td>CNO3W</td>
<td>Soil layer ammonium concentration</td>
<td>mg/l</td>
<td>Calculated</td>
</tr>
<tr>
<td>CPLABW</td>
<td>Soil layer labile P concentration</td>
<td>mg/l</td>
<td>Calculated</td>
</tr>
<tr>
<td>T_{pot}</td>
<td>Potential transpiration</td>
<td>mm</td>
<td>Calculated</td>
</tr>
<tr>
<td>T_{act}</td>
<td>Actual transpiration</td>
<td>mm</td>
<td>Calculated</td>
</tr>
</tbody>
</table>

Table 5-5. Output variables from the vegetation model.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>Total dry matter</td>
<td>kg/ha</td>
<td>Calculated</td>
</tr>
<tr>
<td>W_{a}</td>
<td>Aboveground dry matter</td>
<td>kg/ha</td>
<td>Calculated</td>
</tr>
<tr>
<td>W_{b}</td>
<td>Belowground dry matter</td>
<td>kg/ha</td>
<td>Calculated</td>
</tr>
<tr>
<td>LAI</td>
<td>Green leaf area index</td>
<td>m² leaf/m² ground</td>
<td>Calculated</td>
</tr>
</tbody>
</table>

Table 5-6. Testing scenarios for temperature functions.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Species</th>
<th>T_{min} [°C]</th>
<th>T_{opt1} [°C]</th>
<th>T_{opt2} [°C]</th>
<th>T_{max} [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>Bahia</td>
<td>7</td>
<td>28</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Floralta</td>
<td>7</td>
<td>28</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Panicum</td>
<td>7</td>
<td>28</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Bahia</td>
<td>7</td>
<td>28</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Floralta</td>
<td>0</td>
<td>21</td>
<td>28</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>Panicum</td>
<td>7</td>
<td>28</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Bahia</td>
<td>7</td>
<td>28</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>Floralta</td>
<td>0</td>
<td>15</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Panicum</td>
<td>7</td>
<td>28</td>
<td>35</td>
<td>45</td>
</tr>
</tbody>
</table>
Figure 5-6. Continuous simulation of surface runoff throughout the simulation period from 1998 to 2003.

Figure 5-7. Continuous simulation of water table depths at land segment 9 throughout the simulation period from 1998 to 2003 (WTD = water table depth; PWD = ponded surface water depth).
Figure 5-8. Continuous simulation of P loads throughout the simulation period from 1998 to 2003.

Figure 5-9. Continuous simulation of N loads throughout the simulation period from 1998 to 2003.
Figure 5-10. Continuous simulation of P concentrations throughout the simulation period from 1998 to 2003.

Figure 5-11. Continuous simulation of N concentrations throughout the simulation period from 1998 to 2003.
Figure 5-12. Comparison of predicted potential aboveground biomass for species in land segment 11 with different temperature functions.
Figure 5-13. Comparison of temperature factors among the three selected species in land segment 11.
Figure 5-14. Species distribution (percent of total aboveground biomass at the end of each year) over land segments for bahia, floralta and panicum throughout the simulation period from 1998 to 2003.
Figure 5-14. Continued
Figure 5-15. Comparisons of continuous simulation of aboveground biomass for all species in the selected land segments 8, 11, and 12 before water retention BMP.
Figure 5-16. Comparisons of continuous simulation of aboveground biomass for all species in the selected land segments 8, 11, and 12 after water retention BMP.
Figure 5-17. Growth limiting factors for bahiagrass in land segment 8 before water retention BMP was applied.
CHAPTER 6
SUMMARY AND CONCLUSIONS

Lake Okeechobee, located at the center of the Kissimmee-Okeechobee-Everglades aquatic ecosystem in south Florida, is experiencing water quality degradation. Non-point agricultural runoff from dairies and cow-calf operations in the northern watershed of the lake is considered to be the primary source of excess phosphorus (P) loading discharged into the lake. In order to protect the water quality of Lake Okeechobee and reach environmental restoration goals, a variety of alternative land management practices have been implemented in the Lake Okeechobee watersheds. To evaluate the effectiveness of those practices, a coupled ecohydrological model integrating hydrology, nutrient and vegetation dynamics was developed.

The coupled model was developed within the Java-based, object-oriented framework of the existing ACRU2000 model (Campbell et al., 2001; Clark et al., 2001; Kiker and Clark, 2001). The primary objective of this study was to develop a coupled modeling system capable of simulating hydrology, nutrient and vegetation dynamics simultaneously for south Florida flatwoods watersheds that incorporate wetlands, uplands and transition zones. In this effort, a hydrologic simulation model capable of multi-directional spatial simulation of surface and subsurface water movement was first developed (Chapter 3). The existing nutrient components in ACRU2000 were modified to enable multi-directional spatial transport of N, P, and conservative solute (Chapter 4). Finally, a vegetation dynamics simulation model was developed to couple with the
hydrologic and nutrient models to enable the simulation of the plant growth dynamics under the impacts of changes in water and nutrient availability (Chapter 5).

**Hydrologic Simulation Model**

The hydrologic model capable of multi-directional spatial simulation was developed based on the existing hydrologic model in ACRU2000 by adding new hydrologic components and modifying the existing components. New components include an overland flow component capable of spatial surface water exchange between land segments and a lateral groundwater component capable of spatial soil water exchange between saturated soils of adjacent land segments. These components are important in that they link different land segments together as an entity through lateral water movement and provide the pathways capable of spatial nutrient transport.

A simulation sequence analysis was conducted to analyze the effect of simulation sequence on model predictions, and also to compare with well-known physically based models (MIKE SHE and MODFLOW). Results indicate that different simulation sequences do lead to slightly different simulation results, but they are all consistent when compared with MIKE SHE (DHI, 2004). The results also indicate that the simulation sequence following the expected flow directions based on topography should be chosen when there are multiple combinations of simulation sequence to choose from.

A test was conducted for the Dry Lake Dairy #1 site in the Kissimmee River Basin, Florida to compare the capacity of the modified ACRU2000 hydrologic model in simulating surface runoff and groundwater table to those predicted by the lumped FHANTM model. From the comparisons and statistical analyses, it can be concluded that the modified ACRU2000 hydrologic model is capable of adequately simulating overland flow and lateral groundwater flow at the Dry Lake Dairy #1 site, but the
modified ACRU2000 model is not better than FHANTM. It is possible that ACRU2000 would perform better if it were calibrated to the observed data, particularly if sufficient data were available to calibrate spatially distributed parameters.

**Nutrient Simulation Model**

The nutrient model capable of multi-directional spatial transport of N, P and conservative solute was developed based on the existing nutrient module ACRU-NP (Campbell et al., 2001) in the ACRU2000 modeling system by adding new lateral transport nutrient components.

In order to investigate the accuracy of the conservative solute transport component, the hypothetical scenario test was conducted by comparing with a particle tracking model PMPATH (Chiang and Kinzelbach, 2005). The test results indicate that the solute transport predicted by the modified ACRU2000 is in reasonable agreement with those by PMPATH. Due to the constraints of PMPATH in simulating solute concentration, the model performance in predicting conservative solute is qualitative.

To evaluate the complete performance of the coupled hydrologic and nutrient model, an application was conducted for the beef cattle pastures at Buck Island Ranch, Lake Okeechobee Basin, Florida. A complete model testing procedure was performed including model calibration, verification, and sensitivity analysis using the measured data over a 6-year period. The sensitivity analyses indicated that the hydrologic parameters including crop coefficient, porosity, and restrictive layer hydraulic conductivity are the most sensitive parameters to the hydrologic response. The sensitivities of nutrient parameters tend to be more site-specific. Neither P nor N responses was found to be sensitive to either stocking or fertilizer rate for any site in this application. Rainfall N and P are the two most sensitive parameters to the N and P load responses, respectively.
for the low background nutrient winter pasture site, while and the active P and active N are the two most sensitive parameters for the high nutrient background summer pasture site. Statistics were calculated to evaluate the model performance for calibration and verification. The comparison between statistics obtained using the predictions from ACRU2000 and FHANTM indicate that the modified ACRU2000 did a much better job in simulating hydrologic and nutrient processes. Results indicate that the coupled model can predict hydrologic variables (surface runoff and groundwater elevations) with high accuracy, but that it predicts nutrient loads (N and P) with relatively low accuracy. However, it is difficult to evaluate the model performance on its nutrient simulation capacities based on the limited nutrient observations available. Future work may be needed to sufficiently judge the model performance, especially with regards to nutrient simulation.

Vegetation Dynamics Simulation Model

The vegetation dynamics simulation model was developed, within the framework of previously developed hydrologic and nutrient models, to simulate plant growth for pasture and wetlands species. In the model, solar radiation and temperature are considered to be the major drivers to predict plant growth while environmental impacts, expressed in stress factors (nutrient deficiency and water availability), determine if the plant can grow at its potential rate. Due to the lack of vegetation data available for flatwoods soils, the testing of this model was based on a hypothetical scenario of water retention BMP scenario at summer pasture S4 at the Buck Island Ranch. The simulated results indicate that temperature sensitivities among species are needed to correctly simulate the plant growth. The hypothetical scenario demonstrated that wetlands species, represented by panicum, can tolerate prolonged water logged soil conditions much better
than transition zone and upland species represented by floralta and bahia, and that floralta is more tolerant in those conditions than bahia. However, further testing is needed when sufficient reliable vegetation data become available.

Implications of the Research

As the first working version, the multi-directional spatial, ecohydrological simulation model marks a significant step in adapting the existing ACRU2000 model to better represent hydrology, nutrients and vegetation dynamics for south Florida flatwoods watersheds. Viable mechanisms have been added to enable simulation of some of the unique aspects of flatwoods hydrology. Adaptation to other watersheds or soil conditions at different temporal and spatial scales should be simple using adjusted parameters or by adding relevant process components into this version. However, additional testing and calibration are still needed to improve the robustness of the model for general use in the future.

Future Research Recommendations

The following recommendations are made for those who may be interested in continuing this work in the future.

Model Pre- and Post-processing Capacity

A user graphical interface (GUI) program capable of model pre- and post-processing should be added into the modified ACRU2000. This is especially necessary when the model runs in larger watersheds where more land segments must be defined and parametertized. In the current version, each land segment requires its own land segment input file that includes all required initial, boundary and parameter data. The data required in this input file may confuse users without detailed knowledge of the model structure. In addition, increasing the number of land segments leads to a tremendous
workload in preparing these land segment input files, as well as for adjusting parameters
required in model calibration and sensitivity analysis. Pre-processing capacity providing
a simple interface would make this process more efficient.

Furthermore, a post-processing program is necessary as well. The current version
of the model generates output files by land segments. When users need to compare
output variables over land segments, this must be done through spreadsheet software. It
is difficult to observe the simulation results immediately without additional tedious and
troublesome work to process the outputs. Additionally, the current output procedures do
not allow output of integer variables. This deficiency should be corrected.

**Use Consistent Units for Parameters and Variables**

Use of consistent units throughout the modeling system is necessary to make use of
the model easier and to minimize input errors. Unfortunately, different unit systems still
exist in the current versions of ACRU2000.

**Documentation**

A complete documentation regarding the modifications and additions since the
version of ACRU (v3.00) should be completed to provide the potential users an updated
manual.

**Potential Changes to Existing Objects**

A redesign for the control object (AAcrv2000StandardProcesses) should be
considered. This object is used to determine what processes are to be added in the
execution lists (both vertical and horizontal). Currently, by switching the option variable,
a specific process can be added on or taken off from a list for each land segment.
However, this object is becoming complicated and it may be confusing for users to
customize their own process lists.
Another model input control object (AOldNewAcruVariableReference) is used to establish a reference/mapping relationship between the DData object with the CComponent object for all relationships in the model. The huge collection of hard-coded relationships in this object has made it very cumbersome to understand. Use of an input file, instead of hard-coded relationships in this object, could be one way to improve the situation.

**Sub-Daily Time Step**

An incompatibility in the spatial and temporal resolution is a significant impediment to a robust coupled modeling system that involves different processes having varied temporal scales. The capacity to operate with flexible time steps is necessary, especially when the model is applied in much smaller/larger catchments. A capacity that would allow the model to run in a pre-specified global time step for the entire model, but also allows specific model processes to run in their own local time steps, would make the entire model more efficient and physically reasonable.

**Herbivore Movement Module**

A cattle roaming component should be added to better represent the impacts of grazing on nutrient cycling and plant growth dynamics in this model. This is especially important if the model will be used to investigate the effectiveness of stocking-related BMPs.

**Hydrologic Model**

Hydrologic model should be tested for a wider range of conditions, including more physical locations, larger watersheds and a wider range of runoff conditions.
Nutrient Model

The biased predictions of nutrient concentrations in surface runoff in this research demonstrate that the mechanisms for simulating nutrient cycling need further improvement. Methods for partitioning nutrients between the soil and water phases and methods for dealing with the nutrients released from waste decomposition may require further development.

Vegetation Model

The entire vegetation model should be further evaluated before it is used in a predictive capacity. Components for root length and root biomass distribution dynamics should be added so that species-specific evapotranspiration and nutrient uptake can be more accurately simulated. An algorithm for plant height determination should also be added to enable a feedback relationship between surface runoff and a dynamic roughness coefficient. Moreover, a start-up mechanism for new species initiation in land segments is especially necessary so that spatial expansion across land segments can be modeled and plant competition can be more thoroughly considered. Finally, a herbiore movement model should be developed to simulate the impacts of cattle behavior and grazing performance on vegetation growth.
APPENDIX A
FLOW CHART FOR THE COUPLED MODELING SYSTEM AND MODEL PROCESSES

START

Open I/O Files

Input Model Data

A → Vertical Hydrologic Processes
B → Vertical Vegetation Processes
C → Vertical Nutrient Processes

No → Last Land Segment

Yes →

D → Lateral Hydrologic Processes
E → Lateral Nutrient Processes

No → Last Land Segment

Yes →

Last Day of Simulation Loop

No →

Yes

End

Note: The upper-case letters indicate expandable tree flow charts. (The process objects included are those used for the coupled multi-directional spatial simulation and do not include all existing processes in the original ACRU2000 model.)
PInitialiseSoilUFOptionHWT
PStorageLimited Redistribution
PFindNewPondedWaterDepth
PCheckWaterBalance
PMeanClimateTemp
PRainfallAllCorrection
PInitialiseRainfallAll
PUpwardFlux
PDeepSeepage
PObsDailyAPanEvap
PReferencePotEvapCorrection
PVegInterceptionEvap
PPondedWaterEvaporation
PSetCropCoefficient(PMDSSSerpCropCoefficient)
PRootDistributionFunction
PSuperSimpleEvaporation(PMDSSEvaporation)
PVegInterception
PLandSegRainfallAll
PStorageLimitedInfiltration
PFindNewWaterTableDepth
PStorageLimitedRedistribution
PFindNewPondedWaterDepth

PMDSSWaterLogging
PMDSSNStress
PMDSSPSTress
PGrowthReductionFactor
PDryMatterProductivity
PPlantSenescence
PLeafAreaIndex
PMDSSOrganicMatterDecay
PDeter min eLayer PresssureHeads
PMDSSInitializeNutrients
PMDSSNutrientInputs
PDeadBiomassNutrientTransfer
PConsumedVegetationNutrientTransfer
PAnimalDigestion
PAnimalFeces
PNPlantUptakeFixation
PPlantUptake
PEvaporationTransport
PMean SoilTemp
PHWTAmmoniation
PHWTNitrification
PHWTMineralization
PHWTImmobilization
PHarvest
PVolatilization
PTillage
PHWTSubsurfaceTransport
PMixingZoneExchangeModel
PHWTDenitrification
PConservativeSoluteInputs
PConservativeSoluteEvaporationTransport
PConservativeSoluteSubsurfaceTransport
PConservativeMixingZoneExchangeModel
PCalcOverlandFlow
PCalcLateralGroundwaterFlow
E \rightarrow \left\{ \begin{align*}
\text{PMDSSSurfaceTransport} \\
\text{PMDSSSubsurfaceTransport} \\
\text{PMDSSConservativeSoluteSurfaceTransport} \\
\text{PMDSSConservativeSoluteSubsurfaceTransport}
\end{align*} \right. 
APPENDIX B
FLOW CHART OF OVERLAND FLOW SIMULATION

Start

Information Initialization

Ponded Water Depth ≤ Maximum Depressional Storage

Initialization of Current Adjacent Land Segment

Water Slope ≤ 0.0

Overland Flow Calculation

Last Land Segment?

Storage Apportionment Check

Overland Flow Transfer

End
APPENDIX C
FLOW CHART OF LATERAL GROUNDWATER FLOW SIMULATION

Start

Information Initialization

Information Initialization for Adjacent Land Segment

Lumped Groundwater Flow Calculation

Last Land Segment?

No

Yes

Storage Apportionment Check

Lumped Lateral Flow > 0.0?

No

Yes

Split Lumped Lateral Flow into Layer Flow

Transfer Layer Flow

Update Air Volume for Source and Destination Land Segments

No

Last Land Segment?

Yes

Update Water Table for Source and Destination Land Segments

End
APPENDIX D
LISTS OF NEW AND MODIFIED OBJECTS

New objects listed below mean they did not exist but were added through this research; modified objects mean they existed in the previous model or were created by other modelers but were changed to fit the multi-directional spatial simulation model. Also, hereafter the multi-directional spatial simulation option is called MDSS for short.

**New Model Objects**

**MAcrue2000ModifiedStandard**
This model object is the starting point for the model with a main method inside. It is created to decide how model input data, components, and processes are structured and in what mode the model will be executed. This object allows the model to run either with a lumped mode (MDSS = 0) or a multidirectional distributed mode (MDSS = 1).

**New Process Objects**

**PAdjustOverlandFlow**
This process object is used when the MDSS option is on (MDSS = 1). The major function of this process object is to compare calculated potential overland flow for each adjacent land segment with available amount of surface water storage in the source land segment to guarantee the conservation of mass. If potential overland flow is greater than available amount, then adjustments have to be conducted.

**PAdjacentSpatialUnits**
This process object is used when the MDSS option is on (MDSS = 1). The major function of this process object is to establish the relationships among adjacent land segments for one source land segment according to the boundary conditions, which is used to support the simulation of overland flow.

**PCalcLateralGroundwaterFlow**
This process object is invoked when the MDSS option is on (MDSS = 1). The major function of this object is to calculate the lateral groundwater flows between the saturated soils of two neighbouring land segments and transfer the lateral flows. Darcy's Law is used to estimate the lumped lateral groundwater flow when the hydraulic gradient exists between two saturated soils. Then, the lumped flow is split into the layer flows to those soil layers that contains and is below the current water table of source land segment. The layer lateral flow is transferred layer by layer.
PCalcOverlandFlow
This process object is used when the MDSS option (MDSS = 1) is on. It is designed to calculate overland flows and then transfer the flows to the adjacent land segments.

PCalcWaterBalance
This process is designed to check the daily water balance for both surface and subsurface water for each land segment.

PDryMatterProductivity
This process is invoked when the vegetation simulation option (VEGOPT = 1) is on. This process object is designed to calculate daily biomass productivity for each species in one land segment on the assumption of the plant growth is driven by the climate variables (radiation and temperature). The actual biomass is estimated by multiplying the potential biomass with the growth reduction factor (the minimum among water stress, water logging, and P and N stress factors). Additionally, the actual biomass is partitioned between the above- and below-ground biomass for the use of other vegetation processes.

PFindNewPondedWaterDepth
This process object is designed to find out the current surface ponded water depth. It is called twice in the vertical process list, at the beginning and the end of a given day, before the horizontal processes are executed.

PGrowthReductionFactor
This process is invoked when the VEGOPT option is on. This process object is used to calculate the dry matter growth reduction factor that is a minimum among water stress, water logging, and N and P stress factors. It will be invoked when the VEGOPT option is on.

PLLeafAreaIndex
This process object is used to calculate the daily green leaf area index due to new growth, harvest, grazing, burn and senescence for each vegetation species in each land segment. It will be invoked when the VEGOPT option is on.

PManningRoughnessCoefficient
This process object is used to calculate the manning roughness coefficient according to an approximate method (Fitz et al., 1996) that assume the coefficient is a function of sediment type, plant height and surface water depth.

PMDSSSurfaceTransport
This process object is used when the MDSS option (MDSS = 1) is on. It is used to calculate and transport ammonium N, nitrate N, and labile P carried by surface runoff.

PMDSSSubsurfaceTransport
This process object is used when the MDSS option (MDSS = 1) is on. It is used to calculate and transport ammonium N, nitrate N, and labile P carried by groundwater flow.

**PMDSSConservativeSoluteSurfaceTransport**

This process object is used when the MDSS option (MDSS = 1) is on. It is used to calculate and transport conservative solute carried by surface runoff.

**PMDSSConservativeSoluteSubsurfaceTransport**

This process object is used when the MDSS option (MDSS = 1) is on. It is used to calculate and transport conservative solute carried by subsurface groundwater.

**PMDSSEvapoTranspiration**

This process is used when the VEGOPT option is selected. It is designed to calculate evapotranspiration by multiple species from one land segment by using a very simple method that is identical to that used in DRAINMOD/FHANTM. Potential ET is applied from the top down, reducing soil layers to the wilting point before moving to the next layer. The actual ET is equal to potential ET as long as there is water available.

**PMDSSInitializeNutrients**

This process object is used when the MDSS option (MDSS = 1) is on. It was modified according to PInitalizeNutrient. This process handles initialization of nutrient flux records, plant characteristics and other nutrient-related parameters as defaults when measured values are not available. If soil nutrient data are available for local conditions (soils), the model user should input those values and they will override the generalized estimates generated by the model. Also, the modified object enables to update the N fraction daily.

**PMDSSNutrientInputs**

This process object is used when the MDSS option (MDSS = 1) is on. It was modified from PHWTNutrientInputs to make it more applicable for multi-directional spatial simulation and enable to consider the time series inputs. This process handles nutrient inputs to the watershed system through rainfall, fertilizer, and animal wastes.

This process was remodified from PHWTNutrientInputs and PNutrientInputs to make it more applicable for multi-directional spatial simulation and consider time series events, such as fertilizer, animal waste, etc. Major changes include:

1. Runoff is included only when the model runs in a lumped mode since at this stage runoff have not been simulated when the MDSS option is on.

2. Modify the design in PNutrientsInputs where fertilizer and animal waste applications cannot simultaneously occur. The modification enables consideration of both.

3. Enable the application depth for fertilizer and animal waste to be different. The original related data objects were modified into time-series data objects to handle the potential events.
PMDSSNPlantUptakeFixation
This process object is used when the MDSS option (MDSS = 1) is on. This process calculates the N uptake by multiple plant species of ammonium and nitrate from the soil water by transpiration and/or assimilation (fixation) of nitrogen from the atmosphere by leguminous plants. Fixation is not assumed to add nitrogen to the soil until harvest and/or tillage. This process is modified according to the existing process PNPlantUptakeFixation.

PMDSSNstress
This process is invoked when the VEGOPT option is on. This process calculates the soil water N stress factor from 0.0 to 1.0 according to the method by Seligman and Van Keulen (1981).

PMDSSPPlantUptake
This process object is used when the MDSS option (MDSS = 1) is on. This process calculates the uptake by multiple plant species of labile phosphorus from the soil water by transpiration.

PMDSSPStress
This process is invoked when the VEGOPT option is on. This process calculates the soil water P stress factor from 0.0 to 1.0 according to the similar method as the N stress.

PMDSSSetCropCoefficient
This process is invoked when the VEGOPT option is on. This process was modified according to PSetCropCoefficient to meet the needs when multiple plant species exist. The crop coefficient for each species needs to be set up.

PMDSSTillage
This process object is used when the MDSS option (MDSS = 1) is on. This process calculates the effects of soil tillage on N and P forms and their movement. It was modified from PTillage.

PMDSSWaterLogging
This process is invoked when the VEGOPT option is on. This process is designed to calculate the water logging factor (0–1) and the death indicator that indicate the plant will die caused by the long-term water logging.

POverlandFlowTransfer
This process object is used when the MDSS is on (MDSS = 1). Its major function is to transfer the actual overland flows to neighboring land segments.

PPlantSenescence
This process is invoked when the VEGOPT option is on. This process object is designed to calculate the reduction of live biomass both on surface and subsurface by plant senescence. It is assumed that the decline of live biomass into dead biomass is a linear process during the period of plant senescence. The corresponding N and P also are transferred from live biomass pools to dead biomass pools.

**PSoilParameters**

This process is used to estimate the soil mass, phosphorus and ammonium partitioning coefficients for each soil layer when the nutrient option (NUTRI = 1) is turned on.

**PStorageApportionment**

This process object is used when the MDSS option is on (MDSS = 1). Its major function is to calculate the share of available water storage for each potential overland flow from source land segment.

**PSortAdjacentSpatialUnits**

This process object is used when the MDSS option is on (MDSS = 1). The major function of this process object is to arrange the sequence of adjacent land segments that receive potential overland flows in descending order of their boundary heights.

**New Data Objects**

**DAboveGroundBiomassFluxRecord**

Double flux record data object is to store the aboveground dry matter.

**DACRUVegOption**

Integer data object holds the option to determine if the model enables the vegetation dynamic simulation. VEGOPT = 1, enable simulation of vegetation dynamics; VEGOPT = 0, otherwise.

**DAmmoniumPartitioningCoefficient**

Double data object holds the ammonium partitioning coefficient.

**DBelowGroundBiomassFluxRecord**

Double flux record data object is to store the belowground dry matter.

**DBoundaryInflow**

Double data object holding the flow input from outside of simulation domain.

**DBoundaryOption**

Integer array data object holds the boundary option including:

- BOPT = 0, without weir, without downstream stage;
- BOPT = 1, without weir, with downstream stage;
BOPT = 2, with weir, without downstream stage;
BOPT = 3, with weir, with downstream stage;
BOPT = 4, inflow boundary;

**DBoundaryOutflow**
Double data object holding the outflows though the domain boundary.

**DBoundaryWidth**
Double array data object holding the widths of boundaries for one land segment.

**DCriticalLeafAreaIndex**
This daily data class is to store the degree days for each plant species.

**DDaysofWaterlogging**
Integer data object hold the number of successive days of water logged a plant suffers.

**DDaysofWaterloggingLimits**
Integer object holds the maximum number of days that a plant species still grow under the inundated soil conditions.

**DDryMatterPartitioningCoefficient**
Double data object holds the dry matter partitioning coefficient for a specific plant.

**DExtinctionCoefficient**
Double data object holds the extinction coefficient for a specific plant.

**DGrowthReductionFactor**
Double data object is to store the growth reduction factor.

**DHorizontalSaturatedHydraulicConductivity**
Double data object holding the horizontal saturated hydraulic conductivity for soil layers.

**DIncrementOfAboveGroundBiomass**
Double data object is to store the daily increment of aboveground biomass.

**DIncrementOfBelowGroundBiomass**
Double data object is to store the daily increment of belowground biomass.

**DISoilHorizon**
Integer data object hold the integer ID of the soil horizon to indicate which soil horizon a computational soil layer belong to. It is used to choose different formula when calculate the P partitioning coefficient for sandy soils.
**DLabilePPartitioningCoefficient**
Double data object is to store the labile P partitioning coefficient.

**DLayerAmmNUptake**
Double data object is to store the layer ammonium N uptaken by each plant species.

**DLayerLabPUptake**
Double data object is to store the layer labile P uptaken by each plant species.

**DLayerNitNUptake**
Double data object is to store the layer nitrate N uptaken by each plant species.

**DLayerSoilMass**
Double data object is to store the layer soil mass.

**DLateralGroundwaterAmmNLoad**
Double data object holds the ammonium N load leaving out of the simulation domain through the lateral groundwater flow.

**DLateralGroundwaterConservativeSoluteConc**
Double data object holds the concentration of conservative solute in lateral groundwater discharge through the watershed outlet.

**DLateralGroundwaterConservativeSoluteLoad**
Double data object holds the load of conservative solute in lateral groundwater discharge through the watershed outlet.

**DLateralGroundwaterLabPLoad**
Double data object holds the labile P load leaving out of the simulation domain through the lateral groundwater flow.

**DLateralGroundwaterNitNLoad**
Double data object holds the nitrate N load leaving out of the simulation domain through the lateral groundwater flow.

**DLateralGroundwaterOutflow**
Double data object holds the total groundwater discharge through the outlet of the simulation domain.

**DMaximumGrowthTemperature**
Double data object holds the maximum temperature for a specific plant to enable growth.

**DMaxManningRoughness**
Double data object holds the maximum Manning’s roughness coefficient of a land segment.

DMaxSurfaceDepressionStorage
Double data object holds the maximum depressional surface storage on the ground surface of a land segment.

DMDSSConservativeSoluteOption
Integer data object holds the option to determine whether or not the model simulates the multi-directional spatial transport of conservative solute (MDSSCS = 0, turn on multi-directional spatial simulation of conservative solute transport; MDSSCS = 1, turn off).

DMDSpatialSimulationOption
Integer data object holds the option to determine if the model enables the multi-directional spatial simulation (MDSS = 1, turn on multi-directional spatial simulation; MDSS = 0, turn off).

DMinManningRoughness
Double data object holds the minimum Manning’s roughness coefficient of a land segment.

DMinimumGrowthTemperature
Double data object holds the minimum temperature for a specific plant to enable growth.

DMinimumLeafAreaIndex
Double data object holds the minimum leaf area index for a specific plant.

DNumofVegetationSpecies
Integer data object holds the number of vegetation species to be simulated in one land segment.

DNeighbourWidth
Double array data object holds the widths of boundaries between one land segment and its adjacent land segments or outside of the simulation domain.

DOptimum1GrowthTemperature
Double data object holds the first optimum growth temperature for a specific plant.

DOptimum2GrowthTemperature
Double data object holds the second optimum growth temperature for a specific plant.

DOptimumPConcentration
Double data object holds the optimum P concentration for a specific plant to grow.
DOutletLength
Double data object holds the distance from the center of the land segment to downstream or to the external boundary which separates the land segment and downstream.

DOverlandFlow
Double array data object holds the overland flows occurred from source land segment to adjacent land segments.

DOverlandOutflow
Double data object holds the overland flow leaving the simulation domain through the watershed outlet.

DPlantDeathIndicator
Integer data object indicates if a plant will die off the current land segment due to the water logging (= 1 to die; = 0 not to die).

DPlantNPercent
Double data object holds the plant N percent.

DPlantPPercent
Double data object holds the plant P percent.

DPlantSenescenceRate
Double data object holds the fraction of remaining biomass after plant senescence.

DPondedWaterDepth
Double data object holds daily ponded water depth on the ground surface of a land segment.

DPStressFactor
Double data object holds the plant growth stress factor resulting from a shortage of phosphorus in the root zone.

DRUE
Double data object holds the average light use efficiency for a specific plant.

DSenescedAboveGroundBiomass
Double data object holds the senesced aboveground biomass for a specific plant.

DSenescedBelowGroundBiomass
Double data object holds the senesced belowground biomass for a specific plant.

DShootCriticalNConc
Double data class is to store the critical shoot N concentration.

**DShootCriticalPConc**
Double data class is to store the critical shoot P concentration.

**DShootMinimumGrowthNConc**
Double data object holds the minimum shoot N concentration for maintaining plant growth.

**DShootMinimumGrowthPConc**
Double data object holds the minimum shoot P concentration for maintaining plant growth.

**DShootPConcentration**
Double data class is to store the shoot P concentration.

**DSpecificLeafArea**
Double data object holds the specific leaf area ratio for a specific plant.

**DSoilAluminumContent**
Double data object holds the soil aluminum content.

**DSoilMagnesiumContent**
Double data object holds the soil aluminum content.

**DStockingOption**
Integer data object stores the stocking option.

**DStreamLabPConc**
Double data object holds the stream labile P concentration.

**DStreamNitNConc**
Double data object holds the stream nitrate N concentration.

**DStreamAmmNConc**
Double data object holds the stream ammonium N concentration.

**DTemperatureFactor**
Double data class is to store the temperature factor for a specific plant.

**DTotalDryMatter**
Double data class is to store the total dry matter for a specific plant.
**DTotalOutgoingOverlandFlow**
Double data object holds the total outgoing overland flows form one land segment.

**DTotalReverseOverlandFlow**
Double data object holds the total incoming overland flows form outside of a simulation domain.

**DTotalSurfaceConservativeSoluteStorage**
Double data object holds the total conservative solute mass in the surface water of a land segment.

**DTotalSubSurfaceConservativeSoluteStorage**
Double data object holds the total conservative solute mass within the soil water of a land segment.

**DTotalSurfaceWaterStorage**
Double data object holds the total water storage on the surface of a land segment.

**DTotalSubSurfaceWaterStorage**
Double data object holds the total water storage within the soil of a land segment.

**DXcoord**
Double data object holds the x-coordinate of the centroid of a land segment.

**DYcoord**
Double data object holds the y-coordinate of the centroid of a land segment.

**DWaterStressFactor**
Double data class is to store the water stress factor.

**DWaterLoggingFactor**
Double data class is to store the water logging factor.

**DWeirCoefficient**
Double array data object is to hold the weir coefficients.

**DWeirElevation**
Double array data object is to hold the elevation of weir crust above the datum.

**DWeirOption**
Integer array data object is to hold the weir options.

**DWeirWidth**
Double array data object is to hold the widths of weir crust.

**New Module**

**ACRU_Veg**

To contain all plant growth related processes and collect data objects required by the vegetation dynamic simulation model.

**Modified Component Objects**

**CComponent**

To enable to create two separate vertical and horizontal process lists when the model runs with the MDSS (=1) mode, this existing component object was modified by adding instance variables and methods, including five instance variables: firstVerProcess, firstHorProcess, verProcessesList, horProcessedList, and landSegHorProcessList, and ten methods: addVerticalProcesses(PProcess), addHorizontalProcesses(PProcess), setFirstVerticalProcess(PProcess), setFirstHorizontalProcess(PProcess), getDIntegerArray(String), getFirstVerticalProcess(), getFirstHorizontalProcess(), getLandSegHorProcessesList(), runVerticalProcesses(), and runHorizontalProcesses().

**Modified Control Objects**

**AAcrnu2000ModelInput**

Created one instance variable horProcessesList and added two methods including addToHorizontalProcessList(String, String) and getHorizontalProcessesList() to help with creating a horizontal process list.

**AAcrnu2000StandardModelCreator**

Modified the createProcessObjects() and initialiseProcess() methods to enable two separate vertical and horizontal process list to be created.

**AAcrnu2000StandardCComponents**

Modified the addLandSegmentSubComponents() to enable additions of multiple plant species components.

**AAcrnu2000StandardProcesses**

Modified addLandSegmentProcesses() method to decide which processes objects will be put on the vertical and horizontal process lists when the MDSS option is on.

**AOldNewAcruVariableReference**

Hard coded statements to establish the mapping between input and output variables and the component objects which they belong to.

**AProcessCreator**
Created one overloading method, createProcesses(), to create two separate vertical and horizontal process processes lists, and this method will be invoked only when the MDSS option is on.

**Modified Data Objects**

**DDeepSeepageHeadBoundary**
Modified the data object type from DDailyData to DDouble.

**DDryMatterRatio**
Modified the data object type from DDailyData into DDouble.

**DPotentialYield**
Modified the data object type from DDailyData into DDouble.

**DPPlantID**
Modified the data object type from DDailyInteger into DInteger.

**DPPlantNC1**
Modified the data object type from DDailyData into DDouble.

**DPPlantNC2**
Modified the data object type from DDailyData into DDouble.

**DPPlantNitrogenPhosphorusRatio**
Modified the data object type from DDailyData into DDouble.

**DPPlantBiomassFluxRecord**
Added several biomass transfer methods.

**Modified Process Objects**

**PAnimalDigestion**
Deduct the assimilated consumed biomass N and P.

**PConservativeMixingZoneExchangeModel**
Changed startments in the codes to account for the surface runoff when the MDSS option is on. And corrected the unit conversion error.

**PHWTDenitrification**
Added two more formula for the underestimation problems.

**PHWTNutrientInputs**
Changed statements in the codes to account for the surface runoff when the MDSS option is on.

**PHWTSubsurfaceTransport**  
Corrected the unit conversion error.

**PLabilePPartitioningCoefficient**  
Added one overloading method to calculate the phosphorus partitioning coefficient for the specified soil layer using the empirical formula \(Nair et al., 1997\) for Florida flatwoods sandy soils.

**PMeanSoilTemperature**  
Changed the process object to account for the biomass produced by all plants species.

**PMixingZoneExchangeModel**  
Changed some statements in the codes to account for the surface runoff when the MDSS option is on and corrected the unit conversion error in total amount of surface water.

**PNPlantUptakeFixation**  
Added the codes to account for the mass balance check to avoid the rounding errors.

**PPPlantUptake**  
Added the codes to account for the mass balance check to avoid the rounding errors.

**POrganicMatterDecay**  
Corrected the errors in destroying the biomass for the residue layer.
# APPENDIX E
## LISTS OF NEW INPUT AND OUTPUT VARIABLES

Table E-1. New input and output variables required towards the multi-directional spatial simulation beyond the existing variables in ACRU2000.

<table>
<thead>
<tr>
<th>Input</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A\textsubscript{B}G\textsubscript{D}M\textsubscript{1}*</td>
<td>Species specific aboveground biomass</td>
<td>kg/ha</td>
</tr>
<tr>
<td>A\textsubscript{L}SS</td>
<td>Aluminum content for top soil layer</td>
<td>mg/kg</td>
</tr>
<tr>
<td>A\textsubscript{L}1***</td>
<td>Aluminum content for soil layer 1</td>
<td>mg/kg</td>
</tr>
<tr>
<td>B\textsubscript{D}WD(01)**</td>
<td>Boundary width</td>
<td>m</td>
</tr>
<tr>
<td>B\textsubscript{D}OPT(01)**</td>
<td>Boundary option</td>
<td>–</td>
</tr>
<tr>
<td>B\textsubscript{E}G\textsubscript{D}M\textsubscript{1}*</td>
<td>Species specific belowground biomass</td>
<td>kg/ha</td>
</tr>
<tr>
<td>B\textsubscript{O}F</td>
<td>Surface outflow out of the domain through the stream</td>
<td>m\textsuperscript{3}/day</td>
</tr>
<tr>
<td>B\textsubscript{I}F</td>
<td>Boundary inflows</td>
<td>m\textsuperscript{3}/day</td>
</tr>
<tr>
<td>C\textsubscript{R}I\textsubscript{T}IL\textsubscript{A}I</td>
<td>Critical leaf area index</td>
<td>m\textsuperscript{2}/m\textsuperscript{2} ground</td>
</tr>
<tr>
<td>C\textsubscript{O}N\textsubscript{S}ERV</td>
<td>Conservative solute transport option</td>
<td>–</td>
</tr>
<tr>
<td>D\textsubscript{CS}</td>
<td>Initial conservative solute load applied</td>
<td>kg/ha</td>
</tr>
<tr>
<td>D\textsubscript{P}OND</td>
<td>Ponded surface water depth</td>
<td>mm</td>
</tr>
<tr>
<td>E\textsubscript{X}T\textsubscript{C}O\textsubscript{F}1*</td>
<td>Extinction coefficient</td>
<td>–</td>
</tr>
<tr>
<td>F\textsubscript{A}1*</td>
<td>Dry matter partitioning coefficient</td>
<td>–</td>
</tr>
<tr>
<td>G\textsubscript{C}S</td>
<td>Lateral groundwater conservative solute concentration</td>
<td>mg/l</td>
</tr>
<tr>
<td>G\textsubscript{C}S\textsubscript{L}</td>
<td>Lateral groundwater conservative solute load</td>
<td>kg/ha</td>
</tr>
<tr>
<td>I\textsubscript{N}A\textsubscript{B}G\textsubscript{B}I\textsubscript{O}1*</td>
<td>Daily aboveground biomass increment</td>
<td>kg/ha</td>
</tr>
<tr>
<td>I\textsubscript{N}B\textsubscript{E}G\textsubscript{B}I\textsubscript{O}1*</td>
<td>Daily belowground biomass increment</td>
<td>kg/ha</td>
</tr>
<tr>
<td>I\textsubscript{N}L\textsubscript{I\textsubscript{M}I\textsubscript{T}}\textsubscript{1}*</td>
<td>Water logging limit</td>
<td>day</td>
</tr>
<tr>
<td>I\textsubscript{S}H\textsubscript{S}</td>
<td>Soil horizon code for top soil layer</td>
<td>–</td>
</tr>
<tr>
<td>I\textsubscript{S}H\textsubscript{1}***</td>
<td>Soil horizon code for soil layer 1</td>
<td>–</td>
</tr>
<tr>
<td>K\textsubscript{H}S\textsubscript{T}AT\textsubscript{S}\textsubscript{S}</td>
<td>Horizontal saturated hydraulic conductivity for top layer</td>
<td>m/s</td>
</tr>
<tr>
<td>K\textsubscript{H}S\textsubscript{T}AT\textsubscript{1}***</td>
<td>Horizontal saturated hydraulic conductivity for soil layer 1</td>
<td>m/s</td>
</tr>
<tr>
<td>L\textsubscript{G}W\textsubscript{F}</td>
<td>Lateral groundwater outflow out of the domain</td>
<td>m\textsuperscript{3}/day</td>
</tr>
<tr>
<td>L\textsubscript{G}N\textsubscript{ILO}D</td>
<td>Lateral groundwater nitrate nitrogen load</td>
<td>kg/ha</td>
</tr>
<tr>
<td>L\textsubscript{G}A\textsubscript{M}L\textsubscript{O}D</td>
<td>Lateral groundwater ammonium nitrogen load</td>
<td>kg/ha</td>
</tr>
<tr>
<td>L\textsubscript{G}L\textsubscript{P}LO\textsubscript{D}</td>
<td>Lateral groundwater labile phosphorus load</td>
<td>kg/ha</td>
</tr>
<tr>
<td>L\textsubscript{G}C\textsubscript{S}L\textsubscript{O}D</td>
<td>Lateral groundwater conservative solute load</td>
<td>kg/ha</td>
</tr>
<tr>
<td>M\textsubscript{S}D\textsubscript{S}</td>
<td>Maximum surface depressional storage</td>
<td>m</td>
</tr>
</tbody>
</table>
MDSS = Multi-directional spatial simulation option
MDSSCS = multi-directional spatial conservative solute simulation option
MAXROUGH = Maximum Manning’s roughness coefficient m^{1/3}/day
MAXTEMP1* = Maximum plant growth temperature °C
MGSS = Magnesium content for top soil layer mg/kg
MG1*** = Magnesium content for soil layer 1 mg/kg
MINLAI1* = Minimum leaf area index m^2/m^2
MINROUGH = Minimum Manning’s roughness coefficient m^{1/3}/day
MINTEMP1* = Minimum plant growth temperature °C
NUMVEG = Number of plant species in one land segment –
OMSS = Organic matter for top soil layer %
OM1*** = Organic matter for layer 1 %
OPT1TEMP1* = First optimum growth temperature °C
OPT2TEMP1* = Second optimum growth temperature °C
OUTL = Distance from the centroid of land segment to the external boundary. m
PLRSPS = Plant residue P flux record for top soil layer –
PLRSP1*** = Plant residue P flux record for layer 1 –
PLRSNS = Plant residue N flux record for top soil layer –
PLRSN1*** = Plant residue N flux record for layer 1 –
PLBMASS = Plant residue biomass flux record for top soil layer –
PLBMAS1*** = Plant residue biomass flux record for layer 1 –
RAMLOD = Surface runoff ammonium nitrogen load kg/ha
RAMCON = Surface runoff ammonium nitrogen concentration mg/l
RCSC = Surface runoff conservative solute concentration mg/l
RCSL = Surface runoff conservative solute load kg/ha
RF1* = Productivity reduction factor –
RUE1* = Average light use efficiency g MJ/PAR
RLPLOD = Surface runoff labile P load kg/ha
PLPCON = Surface runoff labile P concentration mg/l
RNIILOD = Surface runoff nitrate nitrogen load kg/ha
PNICON = Surface runoff nitrate nitrogen concentration mg/l
SAMMCONC = Stream ammonium nitrogen concentration mg/l
SCRINCONC1* = Shoot critical N concentration g N/g DM
SCRIPCONC1* = Shoot critical P concentration g P/g DM
SENCERATE1* = Plant senescence rate –
SENEAGBIOM1* = Senesced aboveground biomass kg/ha
SENEBGBIOM1* = Senesced belowground biomass kg/ha
SLA1* = Specific leaf area cm^2 leaf/g leaf
SLABCONC = Stream labile phosphorus concentration mg/l
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLR</td>
<td>Specific leaf area ratio</td>
<td>m²/g leaf</td>
</tr>
<tr>
<td>SMINGNCONC1*</td>
<td>Shoot minimum growth N concentration</td>
<td>g N/g DM</td>
</tr>
<tr>
<td>SMINGPCONC1*</td>
<td>Shoot minimum growth P concentration</td>
<td>g P/g DM</td>
</tr>
<tr>
<td>SNITCONC</td>
<td>Stream nitrate nitrogen concentration</td>
<td>mg/l</td>
</tr>
<tr>
<td>SRL</td>
<td>Specific root length</td>
<td>m/g root</td>
</tr>
<tr>
<td>SSH</td>
<td>Specific shoot height</td>
<td>m³/g shoot</td>
</tr>
<tr>
<td>SWS</td>
<td>Stream water stages</td>
<td>m</td>
</tr>
<tr>
<td>TSCSS</td>
<td>Total surface conservative solute storage</td>
<td>kg/ha</td>
</tr>
<tr>
<td>TSSCSS</td>
<td>Total subsurface conservative solute storage</td>
<td>kg/ha</td>
</tr>
<tr>
<td>TSSWS</td>
<td>Total subsurface water storage</td>
<td>m³</td>
</tr>
<tr>
<td>TSWS</td>
<td>Total surface water storage</td>
<td>m³</td>
</tr>
<tr>
<td>TEMPFAC1**</td>
<td>Temperature factor</td>
<td>–</td>
</tr>
<tr>
<td>V1PLNTID*</td>
<td>Plant ID code</td>
<td>–</td>
</tr>
<tr>
<td>V1LEG*</td>
<td>Legume code for plant species</td>
<td>–</td>
</tr>
<tr>
<td>V1PRNNL*</td>
<td>Plant perennial code</td>
<td>–</td>
</tr>
<tr>
<td>V1POTLAI*</td>
<td>Potential leaf area index</td>
<td>m² leaf/ m² ground</td>
</tr>
<tr>
<td>V1DMR*</td>
<td>Dry matter ratio</td>
<td>–</td>
</tr>
<tr>
<td>V1POTYLD*</td>
<td>Potential yield</td>
<td>kg/ha</td>
</tr>
<tr>
<td>V1CNP*</td>
<td>Plant C:N ratio</td>
<td>–</td>
</tr>
<tr>
<td>V1NPR*</td>
<td>Plant N:P ratio</td>
<td>–</td>
</tr>
<tr>
<td>V1NC1*</td>
<td>Plant NC1</td>
<td>–</td>
</tr>
<tr>
<td>V1NC2*</td>
<td>Plant NC2</td>
<td>–</td>
</tr>
<tr>
<td>V1BMAS*</td>
<td>Initial total specie-specific plant biomass</td>
<td>kg/ha</td>
</tr>
<tr>
<td>V1LAI*</td>
<td>Daily species specific leaf area index</td>
<td>m² leaf/ m² ground</td>
</tr>
<tr>
<td>V1WSTFAC*</td>
<td>Daily species specific water stress factor</td>
<td>–</td>
</tr>
<tr>
<td>V1WLTFAC*</td>
<td>Daily species specific water logging factor</td>
<td>–</td>
</tr>
<tr>
<td>V1PSTFAC*</td>
<td>Daily species specific P stress factor</td>
<td>–</td>
</tr>
<tr>
<td>V1NSTFAC*</td>
<td>Daily species specific N stress factor</td>
<td>–</td>
</tr>
<tr>
<td>VEGOPT</td>
<td>Vegetation dynamic simulation option</td>
<td>–</td>
</tr>
<tr>
<td>WCOEFF(01)**</td>
<td>Weir coefficient</td>
<td>–</td>
</tr>
<tr>
<td>WELEV(01)**</td>
<td>Weir elevation</td>
<td>m</td>
</tr>
<tr>
<td>WTDEP</td>
<td>Water table depth for land segment</td>
<td>m</td>
</tr>
<tr>
<td>WWD(01)**</td>
<td>Weir width</td>
<td>m</td>
</tr>
<tr>
<td>XCOORD</td>
<td>X coordinate of the centroid of the land segment</td>
<td>m</td>
</tr>
<tr>
<td>YCOORD</td>
<td>Y coordinate of the centroid of the land segment</td>
<td>m</td>
</tr>
</tbody>
</table>

Species-specific variables. The digit in the variable names indicates the corresponding species type.

**Land segment related variables. The digit in the variable names indicates the corresponding boundary.

***Soil layer related variables. The digit in the variable names indicates the corresponding soil layer.
APPENDIX F
LISTS OF MODEL INPUT FILES

**Overland Flow along a Flat Rectangular Plane**

- cell.csv
- Control.men
- iroder
- LandSeg_1.men through LandSeg_20.men

**Overland and Groundwater Flow over an Axisymmetric Domain**

- cell.csv
- Control.men
- iroder
- LandSeg_1.men through LandSeg_36.men

**Application at Dry Lake Dairy #1, Kissimmee River Basin, Florida**

- cell.csv
- Control.men
- iroder
- LandSeg_1.men through LandSeg_4.men

**Buck Island Application, Lake Okeechobee Basin, Florida**

- For winter pastures 6 and 7
  - cell.csv
  - Control.men
  - iroder
  - LandSeg_1.men through LandSeg_18.men

- For summer pastures 4 and 1
  - cell.csv
  - Control.men
  - iroder
  - LandSeg_1.men through LandSeg_12.men
APPENDIX G
ALGORITHMS OF WATER STORAGE APPORTIONMENT

Case 1: Single Adjacent Land Segment

The basic idea for deciding the available amount for single adjacent neighbor is moving water until the water levels in both sides are equilibrated in case of sufficient water storage available in source land segment. Otherwise, the available amount could be equal to the total available storage. As a matter of fact, the single neighbor could be either land segment or river type spatial unit. In Figure G-1, $A_s$ and $A_d$ are the surface areas of source and adjacent land segment, respectively; $H_s$ and $H_d$ are their corresponding water elevation, respectively; $E_s$ is the surface elevation of source land segment, which includes the surface depressional storage (in depth). $\text{avaAmount}$ is the maximum available amount from source land segment to its neighbor. The formula used to determine the amount for different situations are listed below:

1. If Single Neighbor is of Land Segment Type

A. There is no weir between source land segment and single neighbor

Figure G-1. Single land segment type neighbor receiving overland flow: (A) $H_d \geq E_s$ and (B) $H_d < E_s$. 
$H_d \geq E_s$

$\text{totAvaStorage} = (H_s - H_d) \times A_s$

$\text{avaAmount} = \text{totAvaStorage} \times A_d / (A_s + A_d)$

$H_d < E_s$

$\text{totAvaStorage} = (H_s - E_s) \times A_s$

$\text{receivingVol} = (E_s - H_d) \times A_d$

- If ($\text{totAvaStorage} \geq \text{receivingVol}$)
  
  $\text{avaAmount} = \text{receivingVol} + \left[\text{totAvaStorage} - \text{receivingVol}\right] \times A_d / (A_s + A_d)$

- If ($\text{totAvaStorage} < \text{receivingVol}$)
  
  $\text{avaAmount} = \text{totAvaStorage}$

**B. There is a weir between source land segment and single neighbor**

Assume the elevation of weir crust is higher than the surface elevation of source land segment. In Figure G-2, $E_w$ represents the elevation of the weir crust. $H_d$ is the water elevation in the river type spatial unit.

![Figure G-2. Single river type neighbor receiving overland flow: (A) $H_d \geq E_w$ and (B) $H_d < E_w$.](image)

$H_d \geq E_w$

$\text{avaAmount} = (H_s - H_d) \times A_s \times A_d / (A_s + A_d)$

$H_d < E_w$

$\text{totAvaStorage} = (H_s - E_w) \times A_s$

$\text{receivingVol} = (E_w - H_d) \times A_d$
If (totAvaStorage ≥ receivingVol)
avaAmount = receivingVol + [totAvaStorage - receivingVol] × A_d / (A_s + A_d)

If (totAvaStorage < receivingVol)
avaAmount = totAvaStorage

2. If Single Neighbor is of River Type

A. If there is no weir in between and no downstream water stage data available
avaAmount = (H_s - E_s) × A_s

B. If there is a weir in between and no downstream water stage data available
   ➔ If E_s ≥ E_w
      avaAmount = (H_s - E_s) × A_s
   ➔ If E_s ≥ E_w
      avaAmount = (H_s - E_w) × A_s

C. If there is no weir in between and downstream water stage data available
avaAmount = (H_s - H_{water stage}) × A_s

D. If there is a weir in between and downstream water stage data available
   ➔ If H_{water stage} ≥ E_w
      avaAmount = (H_s - H_{water stage}) × A_s
   ➔ If H_{water stage} < E_w
      avaAmount = (H_s - E_w) × A_s

Case 2: Multiple Adjacent Land Segments

Figure G-2 displays the relationship between a source land segment and its 4 adjacent land segments. Assume all these neighbors receive outflows from the source land segment and the order of water elevationss of these 4 neighbors follows: neighbour 1 > neighbour 2 > neighbour 3 > neighbour 4. Apparently, the water levels of these neighbors are lower than that of source land segment. This diagram only displays one of potential scenarios of the relationships between source land segment and its neighbors.
The actual relationship patterns could be different. The algorithm should be able to handle all these situations.

In Figure G-3 and the following formula, $A_s$ and $A_1$–$A_4$ represent the areas of source land segment and its corresponding neighbors. $H_s$ and $H_1$–$H_4$ are their corresponding water elevations. $E_s$ is the surface elevation of source land segment. $avaAmount_1$–$avaAmount_4$ is the available amount from source land segment to its corresponding neighbors. $totAvaStorage$ is the total available amount from this unit. $receivingVol$ is the volume in a neighbor, which is above its elevation and below the elevation of this unit. $potWLIncrease$ is the potential increase in the water depth in a neighbor. $remainingStorage$ represents the remaining total available amount in this unit. The formula used to determine each available amount for different situations are listed below:

![Figure G-3. Configuration of multiple directional overland flows from source land segment to adjacent land segments.](image-url)
Loop 1 → neighbour 4

1. If neighbour 4 is of land segment type

A. If there is no weir between source land segment and neighbour 4

⇒ If $H_4 \geq E_s$

$\text{totAvaStorage} = (H_s - H_4) \times A_s$

$\text{potWLIncrease} = \text{totAvaStorage} / (A_s + A_4)$

- If $\text{potWLIncrease} \geq \text{boundaryHeightDiff}_{3,4}$

  $\text{avaAmount} 4 = \text{boundaryHeightDiff}_{3,4} \times A_4$

  $\text{remainingStorage} = \text{totAvaStorage} - \text{avaAmount} 4$

- If $\text{potWLIncrease} < \text{boundaryHeightDiff}_{3,4}$

  $\text{avaAmount} 4 = \text{potWLIncrease} \times A_4$

  Break up the loop.

⇒ If $H_4 < E_s$

$\text{totAvaStorage} = (H_s - E_s) \times A_s$

$\text{receivingVol} = (E_s - H_4) \times A_4$

- If $\text{totAvaStorage} \geq \text{receivingVol}$

  $\text{potWLIncrease} = \frac{[\text{receivingVol} + (\text{totAvaStorage} - \text{receivingVol}) \times A_4 / (A_s + A_4)]}{A_4}$

  - If $\text{NBH3} \geq E_s$

    $\text{remainingStorage} = \text{totAvaStorage} - \text{avaAmount} 4 - (\text{NBH3} - E_s) \times A_s$

  - If $\text{NBH3} < E_s$

    $\text{remainingStorage} = \text{totAvaStorage} - \text{avaAmount} 4$

  Break up the loop.

- If $\text{totAvaStorage} < \text{receivingVol}$

  $\text{potWLIncrease} = \text{totAvaStorage} / A_4$

  - If $\text{potWLIncrease} \geq \text{boundaryHeightDiff}_{3,4}$

    $\text{avaAmount} 4 = \text{boundaryHeightDiff}_{3,4} \times A_4$

    $\text{remainingStorage} = \text{totAvaStorage} - \text{avaAmount} 4$

  - If $\text{potWLIncrease} < \text{boundaryHeightDiff}_{3,4}$

    $\text{avaAmount} 4 = \text{potWLIncrease} \times A_4$
Break up the loop.

B. If there is a weir between source land segment and neighbour 4

- If \( H_4 \geq E_{w4} \)
  
  \[
  \text{totAvaStorage} = (H_s - H_4) \times A_s
  \]
  
  \[
  \text{potWLIncrease} = \text{totAvaStorage} / (A_s + A_4)
  \]
  
  - If \( \text{potWLIncrease} \geq \text{boundaryHeightDiff}_{3,4} \)
    
    \[
    \text{avaAmount} 4 = \text{boundaryHeightDiff}_{3,4} \times A_4
    \]
    
    \[
    \text{remainingStorage} = \text{totAvaStorage} - \text{avaAmount} 4
    \]
  
  - If \( \text{potWLIncrease} < \text{boundaryHeightDiff}_{3,4} \)
    
    \[
    \text{avaAmount} 4 = \text{potWLIncrease} \times A_4
    \]
    
    Break up the loop.

- If \( H_4 < E_{w4} \)
  
  \[
  \text{totAvaStorage} = (H_s - E_{w4}) \times A_s
  \]
  
  \[
  \text{receivingVol} = (E_{w4} - H_4) \times A_4
  \]
  
  - If \( \text{totAvaStorage} \geq \text{receivingVol} \)
    
    \[
    \text{potWLIncrease} = (\text{totAvaStorage} - \text{receivingVol}) / (A_s + A_4)
    \]
    
    - If \( \text{potWLIncrease} \geq \text{boundaryHeightDiff}_{3,4} \)
      
      \[
      \text{avaAmount} 4 = \text{receivingVol} + \text{boundaryHeightDiff}_{3,4} \times A_4
      \]
      
      \[
      \text{remainingStorage} = \text{totAvaStorage} - \text{avaAmount} 4
      \]
    
    - If \( \text{potWLIncrease} < \text{boundaryHeightDiff}_{3,4} \)
      
      \[
      \text{avaAmount} 4 = \text{receivingVol} + \text{potWLIncrease} \times A_4
      \]
      
    Break up the loop.
  
  - If \( \text{totAvaStorage} < \text{receivingVol} \)
    
    \[
    \text{avaAmount} 4 = \text{totAvaStorage}
    \]
    
    Break up the loop.

2. If neighbour 4 is of river type

A. If there is no weir in between and no downstream water stage data available

\[
\text{avaAmount} 4 = (H_s - E_s) \times A_s
\]

Break up the loop.

B. If there is a weir in between and no downstream water stage data available

- If \( E_s \geq E_{w4} \)
  
  \[
  \text{avaAmount} 4 = (H_s - E_s) \times A_s
  \]
  
  Break up the loop
If $E_s \geq E_{w4}$
avaAmount 4 = $(H_s - E_{w4}) \times A_s$
Break up the loop

C. If there is no weir in between and downstream water stage data available
avaAmount 4 = $(H_s - H_{\text{water stage}}) \times A_s$

D. If there is a weir in between and downstream water stage data available

→ If $H_{\text{water stage}} \geq E_{w4}$
avaAmount 4 = $(H_s - H_{\text{water stage}}) \times A_s$
Break up the loop
→ If $H_{\text{water stage}} < E_{w4}$
avaAmount 4 = $(H_s - E_{w4}) \times A_s$
Break up the loop

Loop 2 → neighbour 3

1. If neighbour 3 is of land segment type

A. If there is no weir between source land segment and neighbour 3

→ If $H_3 \geq E_s$

potWLIncrease = $\frac{\text{remainingStorage}}{(A_s + A_3 + A_4)}$

☐ If $\text{potWLIncrease} \geq \text{boundaryHeightDiff}_{2,3}$
avaAmount 3 = $\text{boundaryHeightDiff}_{2,3} \times A_3$
avaAmount 4 = avaAmount 4 + $\text{boundaryHeightDiff}_{2,3} \times A_4$
remainingStorage = remainingStorage - $\text{boundaryHeightDiff}_{2,3} \times (A_s + A_3 + A_4)$

☐ If $\text{potWLIncrease} < \text{boundaryHeightDiff}_{2,3}$
avaAmount 3 = potWLIncrease $\times A_3$
avaAmount 4 = avaAmount 4 + potWLIncrease $\times A_4$
Break up the loop.

→ If $H_3 < E_s$

receivingVol = $(E_s - H_3) \times (A_3 + A_4)$

☐ If remainingStorage $\geq$ receivingVol

potWLIncrease = $[\text{receivingVol} + (\text{remainingStorage} - \text{receivingVol}) \times (A_3 + A_4) / (A_s + A_3 + A_4)] / (A_3 + A_4)$

⇒ If $\text{potWLIncrease} \geq \text{boundaryHeightDiff}_{2,3}$
avaAmount 3 = $\text{boundaryHeightDiff}_{2,3} \times A_3$
avaAmount 4 = avaAmount 4 + boundaryHeightDiff₂₃ × A₄

- If NBH₂ ≥ Es
  remainingStorage = remainingStorage - boundaryHeightDiff₂₃ × (A₃ + A₄) - (NBH₂ - Eₛ) × Aₛ
- If NBH₂ < Eₛ
  remainingStorage = remainingStorage - boundaryHeightDiff₂₃ × (A₃ + A₄)

⇒ If potWLIncrease < boundaryHeightDiff₂₃
  avaAmount 3 = potWLIncrease × A₃
  avaAmount 4 = avaAmount 4 + potWLIncrease × A₄
  Break up the loop.

- If remainingStorage < receivingVol
  potWLIncrease = remainingStorage / (A₃ + A₄)
  ⇒ If potWLIncrease ≥ boundaryHeightDiff₂₃
     avaAmount 3 = boundaryHeightDiff₂₃ × A₃
     avaAmount 4 = avaAmount 4 + boundaryHeightDiff₂₃ × A₄
     remainingStorage = remainingStorage - boundaryHeightDiff₂₃ × (A₃ + A₄)
  ⇒ If potWLIncrease < boundaryHeightDiff₂₃
     avaAmount 3 = potWLIncrease × A₃
     avaAmount 4 = avaAmount 4 + potWLIncrease × A₄
     Break up the loop.

B. If there is a weir between source land segment and neighbour 3

⇒ If H₃ ≥ E_w₃
  potWLIncrease = remainingStorage / (Aₛ + A₃ + A₄)

- If potWLIncrease ≥ boundaryHeightDiff₂₃
  avaAmount 3 = boundaryHeightDiff₂₃ × A₃
  avaAmount 4 = avaAmount 4 + boundaryHeightDiff₂₃ × A₄
  remainingStorage = remainingStorage - boundaryHeightDiff₂₃ × (Aₛ + A₃ + A₄)

- If potWLIncrease < boundaryHeightDiff₂₃
  avaAmount 3 = potWLIncrease × A₃
  avaAmount 4 = avaAmount 4 + potWLIncrease × A₄
  Break up the loop.

⇒ If H₃ < E_w₃
  receivingVol = (E_w₃ - H₃) × A₃

- If remainingStorage ≥ receivingVol
potWLIncrease = (remainingStorage - receivingVol) / (A₁ + A₃ + A₄)  

⇒ If potWLIncrease ≥ boundaryHeightDiff₂,₃
avaAmount 3 = receivingVol + boundaryHeightDiff₂,₃ × A₃
avaAmount 4 = avaAmount 4 + boundaryHeightDiff₂,₃ × A₄
remainingStorage = remainingStorage - receivingVol - boundaryHeightDiff₂,₃ × (A₃+A₄)

⇒ If potWLIncrease < boundaryHeightDiff₂,₃
avaAmount 3 = receivingVol + potWLIncrease × A₃
avaAmount 4 = avaAmount 4 + potWLIncrease × A₄
Break up the loop.

☐ If remainingStorage < receivingVol
avaAmount 3 = remainingStorage
Break up the loop.

2. If neighbour 3 is of river type

A. If there is no weir in between and no downstream water stage data available
avaAmount 3 = remainingStorage
Break up the loop.

B. If there is no weir in between and downstream water stage data available
maxStorage = (Hₛ - H_{water stage}) × A₄
⇒ If maxStorage ≥ remainingStorage
avaAmount 3 = remainingStorage
Break up the loop
⇒ If maxStorage < remainingStorage
avaAmount 3 = maxStorage
remainingStorage = remainingStorage - avaAmount 3

C. If there is a weir in between and no downstream water stage data available
⇒ If Eₛ ≥ Eₜ₃
avaAmount 3 = (Hₛ - Eₛ) × Aₛ
Break up the loop
⇒ If Eₛ < Eₜ₃
avaAmount 3 = (Hₛ - Eₜ₃) × Aₛ
Break up the loop
D. If there is a weir in between and downstream water stage data available

- If $H_{\text{water stage}} \geq E_{w3}$
  
  $\text{maxStorage} = (H_s - H_{\text{water stage}}) \times A_s$

  - if $\text{maxStorage} \geq \text{remainingStorage}$
    
    $\text{avaAmount 3} = \text{remainingStorage}$

  - if $\text{maxStorage} < \text{remainingStorage}$
    
    $\text{avaAmount 3} = \text{maxStorage}$

  $\text{remainingStorage} = \text{remainingStorage} - \text{avaAmount 3}$

- If $H_{\text{water stage}} < E_{w3}$
  
  $\text{maxStorage} = (H_s - E_{w3}) \times A_s$

  - if $\text{maxStorage} \geq \text{remainingStorage}$
    
    $\text{avaAmount 3} = \text{remainingStorage}$

  - if $\text{maxStorage} < \text{remainingStorage}$
    
    $\text{avaAmount 3} = \text{maxStorage}$

  Break up the loop

Loop 3 $\rightarrow$ neighbour 2

1. If neighbour 2 is of land segment type

A. If there is no weir between source land segment and neighbour 2

- If $H_2 \geq E_s$
  
  $\text{potWLIncrease} = \text{remainingStorage} / (A_s + A_2 + A_3 + A_4)$

  - if $\text{potWLIncrease} \geq \text{boundaryHeightDiff}_{1,2}$
    
    $\text{avaAmount 2} = \text{boundaryHeightDiff}_{1,2} \times A_2$

    $\text{avaAmount 3} = \text{avaAmount 3} + \text{boundaryHeightDiff}_{1,2} \times A_3$

    $\text{avaAmount 4} = \text{avaAmount 4} + \text{boundaryHeightDiff}_{1,2} \times A_4$

    $\text{remainingStorage} = \text{remainingStorage} - \text{boundaryHeightDiff}_{1,2} \times (A_s + A_2 + A_3 + A_4)$

  - if $\text{potWLIncrease} < \text{boundaryHeightDiff}_{1,2}$
    
    $\text{avaAmount 2} = \text{potWLIncrease} \times A_2$

    $\text{avaAmount 3} = \text{avaAmount 3} + \text{potWLIncrease} \times A_3$

    $\text{avaAmount 4} = \text{avaAmount 4} + \text{potWLIncrease} \times A_4$

  Break up the loop.

- If $H_2 < E_s$
  
  $\text{receivingVol} = (E_s - H_2) \times (A_2 + A_3 + A_4)$
If remainingStorage ≥ receivingVol

\[
potWLIncrease = \frac{[\text{receivingVol} + (\text{remainingStorage} - \text{receivingVol}) \times (A_2 + A_3 + A_4)]}{(A_s + A_2 + A_3 + A_4)} / (A_2 + A_3 + A_4)
\]

\[\Rightarrow\] If potWLIncrease ≥ boundaryHeightDiff_{1,2}

avaAmount 2 = boundaryHeightDiff_{1,2} × A_2
avaAmount 3 = avaAmount 3 + boundaryHeightDiff_{1,2} × A_3
avaAmount 4 = avaAmount 4 + boundaryHeightDiff_{1,2} × A_4

- If NBH1 ≥ Es
  
  remainingStorage = remainingStorage - boundaryHeightDiff_{1,2} × (A_2 + A_3 + A_4) - (NBH1 - E_s) × A_s

- If NBH1 < E_s
  
  remainingStorage = remainingStorage - boundaryHeightDiff_{1,2} × (A_2 + A_3 + A_4)

\[\Rightarrow\] If potWLIncrease < boundaryHeightDiff_{1,2}

avaAmount 2 = potWLIncrease × A_2
avaAmount 3 = avaAmount 3 + potWLIncrease × A_3
avaAmount 4 = avaAmount 4 + potWLIncrease × A_4

Break up the loop.

If remainingStorage < receivingVol

potWLIncrease = remainingStorage / (A_2 + A_3 + A_4)

\[\Rightarrow\] If potWLIncrease ≥ boundaryHeightDiff_{1,2}

avaAmount 2 = boundaryHeightDiff_{1,2} × A_2
avaAmount 3 = avaAmount 3 + boundaryHeightDiff_{1,2} × A_3
avaAmount 4 = avaAmount 4 + boundaryHeightDiff_{1,2} × A_4

remainingStorage = remainingStorage - boundaryHeightDiff_{1,2} × (A_2 + A_3 + A_4)

\[\Rightarrow\] If potWLIncrease < boundaryHeightDiff_{1,2}

avaAmount 2 = potWLIncrease × A_2
avaAmount 3 = avaAmount 3 + potWLIncrease × A_3
avaAmount 4 = avaAmount 4 + potWLIncrease × A_4

Break up the loop.

B. If there is a weir between source land segment and neighbour 2

\[\Rightarrow\] If H_2 ≥ E_{w_2}

potWLIncrease = remainingStorage / (A_s + A_2 + A_3 + A_4)

- If potWLIncrease ≥ boundaryHeightDiff_{1,2}
  
  avaAmount 2 = boundaryHeightDiff_{1,2} × A_2
avaAmount 3 = avaAmount 3 + boundaryHeightDiff_{1,2} \times A_3
avaAmount 4 = avaAmount 4 + boundaryHeightDiff_{1,2} \times A_4
remainingStorage = remainingStorage - boundaryHeightDiff_{1,2} \times (A_s + A_2 + A_3 + A_4)

- If potWLIncrease < boundaryHeightDiff_{1,2}
  avaAmount 2 = potWLIncrease \times A_2
  avaAmount 3 = avaAmount 3 + potWLIncrease \times A_3
  avaAmount 4 = avaAmount 4 + potWLIncrease \times A_4
  Break up the loop.

- If H_2 < E_{w_2}
  receivingVol = (E_{w_2} - H_2) \times A_2
- if remainingStorage ≥ receivingVol
  potWLIncrease = (remainingStorage - receivingVol) / (A_s + A_2 + A_3 + A_4)
  - if potWLIncrease ≥ boundaryHeightDiff_{1,2}
    avaAmount 2 = receivingVol + boundaryHeightDiff_{1,2} \times A_2
    avaAmount 3 = avaAmount 3 + boundaryHeightDiff_{1,2} \times A_3
    avaAmount 4 = avaAmount 4 + boundaryHeightDiff_{1,2} \times A_4
    remainingStorage = remainingStorage - receivingVol - boundaryHeightDiff_{1,2} \times (A_2 + A_3 + A_4)
  - if potWLIncrease < boundaryHeightDiff_{1,2}
    avaAmount 2 = receivingVol + potWLIncrease \times A_2
    avaAmount 3 = avaAmount 3 + potWLIncrease \times A_3
    avaAmount 4 = avaAmount 4 + potWLIncrease \times A_4
    Break up the loop.

- If remainingStorage < receivingVol
  avaAmount 2 = remainingStorage
  Break up the loop.

2. If neighbour 2 is of river type
   A. If there is no weir in between and no downstream water stage data available
      avaAmount 2 = remainingStorage
      Break up the loop.

   B. If there is no weir in between and downstream water stage data available
      maxStorage = (H_s - H_{water stage}) \times A_s
      - If maxStorage ≥ remainingStorage
avaAmount 2 = remainingStorage
Break up the loop

- If maxStorage < remainingStorage
  avaAmount 2 = maxStorage
  remainingStorage = remainingStorage - avaAmount 2

C. If there is a weir in between and no downstream water stage data available

- If $E_s \geq E_{w2}$
  avaAmount 2 = $(H_s - E_s) \times A_s$
  Break up the loop

- If $E_s < E_{w2}$
  avaAmount 2 = $(H_s - E_{w2}) \times A_s$
  Break up the loop

D. If there is a weir in between and downstream water stage data available

- If $H_{\text{water stage}} \geq E_{w2}$
  maxStorage = $(H_s - H_{\text{water stage}}) \times A_s$
  - If maxStorage $\geq$ remainingStorage
    avaAmount 2 = remainingStorage
  - If maxStorage $<$ remainingStorage
    avaAmount 2 = maxStorage
    remainingStorage = remainingStorage - avaAmount 2

- If $H_{\text{water stage}} < E_{w2}$
  maxStorage = $(H_s - E_{w2}) \times A_s$
  - If maxStorage $\geq$ remainingStorage
    avaAmount 2 = remainingStorage
  - If totAvaStorage $<$ remainingStorage
    avaAmount 2 = maxStorage
    Break up the loop

Loop 4 $\rightarrow$ neighbour 1

1. If neighbor 1 is of land segment type
A. If there is no weir in between

- If $H_1 \geq E_s$
  avaAmount 1 = remainingStorage $\times A_1 / (A_s + A_1 + A_2 + A_3 + A_4)$
avaAmount 2 = avaAmount 2 + remainingStorage \times \frac{A_2}{A_1 + A_2 + A_3 + A_4}
avaAmount 3 = avaAmount 3 + remainingStorage \times \frac{A_3}{A_1 + A_2 + A_3 + A_4}
avaAmount 4 = avaAmount 4 + remainingStorage \times \frac{A_4}{A_1 + A_2 + A_3 + A_4}

⇒ If H_1 < E_s

receivingVol = (E_s - H_1) \times (A_1 + A_2 + A_3 + A_4)

□ If remainingStorage ≥ receivingVol

amountToAllNeigh = receivingVol + (remainingStorage - receivingVol) \times (A_1 + A_2 + A_3 + A_4) / (A_s + A_1 + A_2 + A_3 + A_4)
avaAmount 1 = amountToAllNeigh \times \frac{A_1}{A_1 + A_2 + A_3 + A_4}
avaAmount 2 = avaAmount 2 + amountToAllNeigh \times \frac{A_2}{A_1 + A_2 + A_3 + A_4}
avaAmount 3 = avaAmount 3 + amountToAllNeigh \times \frac{A_3}{A_1 + A_2 + A_3 + A_4}
avaAmount 4 = avaAmount 4 + amountToAllNeigh \times \frac{A_4}{A_1 + A_2 + A_3 + A_4}

□ If remainingStorage < receivingVol

avaAmount 1 = remainingStorage \times \frac{A_1}{A_1 + A_2 + A_3 + A_4}
avaAmount 2 = avaAmount 2 + remainingStorage \times \frac{A_2}{A_1 + A_2 + A_3 + A_4}
avaAmount 3 = avaAmount 3 + remainingStorage \times \frac{A_3}{A_1 + A_2 + A_3 + A_4}
avaAmount 4 = avaAmount 4 + remainingStorage \times \frac{A_4}{A_1 + A_2 + A_3 + A_4}

B. If there is a weir in between

⇒ If H_1 ≥ E_w

avaAmount 1 = remainingStorage \times \frac{A_1}{A_s + A_1 + A_2 + A_3 + A_4}
avaAmount 2 = avaAmount 2 + remainingStorage \times \frac{A_2}{A_s + A_1 + A_2 + A_3 + A_4}
avaAmount 3 = avaAmount 3 + remainingStorage \times \frac{A_3}{A_s + A_1 + A_2 + A_3 + A_4}
avaAmount 4 = avaAmount 4 + remainingStorage \times \frac{A_4}{A_s + A_1 + A_2 + A_3 + A_4}

⇒ If H_1 < E_w

receivingVol = (E_w - H_1) \times A_3

□ If remainingStorage ≥ receivingVol

amountToAllNeigh = (remainingStorage - receivingVol) \times \frac{A_1 + A_2 + A_3 + A_4}{A_s + A_1 + A_2 + A_3 + A_4}
avaAmount 1 = receivingVol + amountToAllNeigh \times \frac{A_1}{A_1 + A_2 + A_3 + A_4}
avaAmount 2 = avaAmount 2 + amountToAllNeigh \times \frac{A_2}{A_1 + A_2 + A_3 + A_4}
avaAmount 3 = avaAmount 3 + amountToAllNeigh \times \frac{A_3}{A_1 + A_2 + A_3 + A_4}
avaAmount 4 = avaAmount 4 + amountToAllNeigh \times \frac{A_4}{A_1 + A_2 + A_3 + A_4}

□ If remainingStorage < receivingVol

avaAmount 1 = remainingStorage
2. If neighbour 1 is of river type

A. If there is no weir in between and no downstream water stage data available
   \[ \text{avaAmount } 1 = \text{remainingStorage} \]

B. If there is a weir in between and no downstream water stage data available
   \[ \text{If } E_s \geq E_{w1} \]
   \[ \text{avaAmount } 1 = (H_s - E_s) \times A_s \]
   \[ \text{If } E_s < E_{w1} \]
   \[ \text{avaAmount } 1 = (H_s - E_{w1}) \times A_s \]

C. If there is no weir in between and downstream water stage data available
   \[ \text{maxStorage} = (H_s - H_{\text{water stage}}) \times A_s \]
   \[ \text{If } \text{maxStorage} \geq \text{remainingStorage} \]
   \[ \text{avaAmount } 1 = \text{remainingStorage} \]
   \[ \text{If } \text{maxStorage} < \text{remainingStorage} \]
   \[ \text{avaAmount } 1 = \text{maxStorage} \]

D. If there is a weir in between and downstream water stage data available
   \[ \text{If } H_{\text{water stage}} \geq E_{w1} \]
   \[ \text{maxStorage} = (H_s - H_{\text{water stage}}) \times A_s \]
   \[ \text{If } \text{maxStorage} \geq \text{remainingStorage} \]
   \[ \text{avaAmount } 1 = \text{remainingStorage} \]
   \[ \text{If } \text{maxStorage} < \text{remainingStorage} \]
   \[ \text{avaAmount } 1 = \text{maxStorage} \]
   \[ \text{If } H_{\text{water stage}} < E_{w1} \]
   \[ \text{maxStorage} = (H_s - E_{w1}) \times A_s \]
   \[ \text{If } \text{maxStorage} \geq \text{remainingStorage} \]
   \[ \text{avaAmount } 1 = \text{remainingStorage} \]
   \[ \text{If } \text{maxStorage} < \text{remainingStorage} \]
   \[ \text{avaAmount } 1 = \text{maxStorage} \]
Nomenclature

$A_s$  Area of source land segment
$A_d$  Area of destination land segment
$A_1$  Area of adjacent land segment 1
$A_2$  Area of adjacent land segment 2
$A_3$  Area of adjacent land segment 3
$A_4$  Area of adjacent land segment 4
$amountToAllNeigh$  Amount of water for all adjacent land segments
$avaAmount$  Allocated amount of storage for single adjacent land segment
$avaAmount 1$  Accumulated amount of storage for adjacent land segment 1
$avaAmount 2$  Accumulated amount of storage for adjacent land segment 2
$avaAmount 3$  Accumulated amount of storage for adjacent land segment 3
$avaAmount 4$  Accumulated amount of storage for adjacent land segment 4
$boundaryHeightDiff_{1,2}$  Difference of boundary heights between land segment 1 and 2
$boundaryHeightDiff_{2,3}$  Difference of boundary heights between land segment 2 and 3
$boundaryHeightDiff_{3,4}$  Difference of boundary heights between land segment 3 and 4
$H_s$  Water level of source land segment
$H_d$  Water level of destination land segment
$H_1$  Water level of adjacent land segment 1
$H_2$  Water level of adjacent land segment 2
$H_3$  Water level of adjacent land segment 3
$H_4$  Water level of adjacent land segment 4
$H_{water stage}$  Downstream water stage
$E_s$  Elevation of source land segment
$E_{w1}$  Weir elevation between source land segment and land segment 1
$E_{w2}$  Weir elevation between source land segment and land segment 2
$E_{w3}$  Weir elevation between source land segment and land segment 3
$E_{w4}$  Weir elevation between source land segment and land segment 4
$maxStorage$  Maximum storage can be transferred
$NBH1$  Boundary height between land segment 1 and source land segment
$NBH2$  Boundary height between land segment 2 and source land segment
$NBH3$  Boundary height between land segment 3 and source land segment
$receivingVol$  Portion of water volume is allocated to an adjacent land segment
$remainingStorage$  Water storage has no been allocated
$potWLIncrease$  Potential water level increase with a given amount of water input
$totAvaStorage$  Total available amount if water storage in source land segment
LIST OF REFERENCES


Heatwole CD. 1986. Field and basin scale water quality models for evaluating agricultural nonpoint pollution abatement programs in a south Florida Modified CREAMS hydrology model for Coastal Plain watersheds. Trans. ASAE 30(4): 1014-1022.


McDonald MG and Harbaugh AW. 1996. MODFLOW: the modular three dimensional finite-difference ground water flow model. USGS.


Sims R. 2004. Performance evaluation of the field hydrologic and nutrient transport model (FHANTM 2.0) on beef pastures at Buck Island Ranch, Florida. A technical paper presented to the graduate school of the University Of Florida in partial fulfillment of the requirements for the degree of master of interdisciplinary ecology. University of Florida.


BIOGRAPHICAL SKETCH

Lei Yang was born in Henan province, People’s Republic of China, in a family led by fairly open-minded parents who always encourage their kids to pursue what they dreamed in their lives. Lei graduated from Hohai University, China, with a BS in 1991 and a MS in 1994 majoring in hydrology and water resources engineering. Upon the completion of her MS, she was then employed as a civil engineer in the China Institute of Water Resources and Hydropower Research for close to three years. Excelling in research projects developing flood inundation and mitigation simulation models, in October 1997 she was recommended to join a research student program in Kyoto University, Japan, financed with a Japanese MOBUSHO scholarship. With the experience gained during that period, Lei started to pursue one of her dreams that she wanted to reach a higher professional level in the field of hydrology and water resources through advanced study. In August 2000, she joined the Agricultural and Biological Engineering Department at the University of Florida as a graduate research assistant and a PhD student.