TECHNICAL REPORT NO. 96

Refinement of Critically Needed Assessment Tools for Tile Drainage Phosphorus Loading in the Lake Champlain Basin

June 2020
Final Report

Prepared by:
Michael Winchell
Stone Environmental

For:
The Lake Champlain Basin Program and
New England Interstate Water Pollution Control Commission

This report was funded and prepared under the authority of the Lake Champlain Special Designation Act of 1990, P.L. 101-596 and subsequent reauthorization in 2002 as the Daniel Patrick Moynihan Lake Champlain Basin Program Act, H. R. 1070, through the US EPA. Publication of this report does not signify that the contents necessarily reflect the views of the states of New York and Vermont, the Lake Champlain Basin Program or the US EPA.

The Lake Champlain Basin Program has funded more than 90 technical reports and research studies since 1991. For complete list of LCBP Reports please visit:
http://www.lcbp.org/media-center/publications-library/publication-database/

NEIWPCC Job Code: 994-002-001

Final Report: Refinement of Critically Needed Assessment Tools for Tile Drainage Phosphorus Loading in the Lake Champlain Basin

PROJECT NO.

18-134

PREPARED FOR:

Matthew Vaughan/ *NEIWPCC Environmental Analyst, LCBP Technical Coordinator*
Lake Champlain Basin Program
54 West Shore Road
Grand Isle / VT / 05458
mvaughan@lcbp.org
802.372.0216

SUBMITTED BY:

Michael Winchell / *Vice President, Senior Environmental Modeler*
Stone Environmental, Inc.
535 Stone Cutters Way
Montpelier / VT /05602
mwinchell@stone-env.com
802.229.1882

Acknowledgements

This project was funded by an agreement awarded by the Environmental Protection Agency (EPA) to the New England Interstate Water Pollution Control Commission (NEIWPCC) in partnership with the Lake Champlain Basin Program (LCBP). NEIWPCC manages LCBP's personnel, contract, grant, and budget tasks and provides input on the program's activities through a partnership with the LCBP Steering Committee.

Although the information in this document has been funded wholly or in part by the United States Environmental Protection Agency under agreement LC00A00377 to NEIWPCC, it has not undergone the Agency's publications review process and therefore, may not necessarily reflect the views of the Agency and no official endorsement should be inferred. The viewpoints expressed here do not necessarily represent those of NEIWPCC, the LCBP Steering Committee, or EPA, nor does mention of trade names, commercial products, or causes constitute endorsement or recommendation for use.

Title and Approval Page

Document Title

Refinement of Critically Needed Assessment Tools for Tile Drainage P Loading in the Lake Champlain Basin: Final Report

Document Prepared by

Stone Environmental, Inc., 535 Stone Cutters Way, Montpelier, Vermont 05602
Newtrient LLC, 10255 W. Higgins Road Suite 900, Rosemont, IL 60018

Document Preparer Approvals

Michael Winchell, Vice President & Senior Environmental Modeler, Stone Environmental, Inc.

6/2/2020

Signature Date

Jody Stryker, Senior Environmental Modeler, Stone Environmental, Inc.

By my signature, I hereby certify that I have reviewed this document.

6/2/2020

Signature Date

Chris Kopman, Chief Financial Officer, Newtrient LLC

By my signature, I hereby certify that I have reviewed this document.

6/2/2020

Signature Date

Executive Summary

The goal of this project was to develop a robust APEX model capable of representing edge-of-field P loads (both via surface transport and tile drainage) and to use this model to investigate the impacts of innovative manure management technologies on P loads. This work addresses the need for quantification of P loads from tile drain flow under various conditions, as well as provides a basis for comparing P load from tile flow and surface runoff, and for evaluating factors influencing P movement in tile drainage. It also provides a quantitative assessment of the potential value of manure management technologies in reducing P loads from agricultural fields. Innovative manure management may play a role in improving water quality outcomes at the farm and basin-scale.

Five Vermont edge-of-field sites, six Vermont tile drained sites, and one New York site (with both tile and edge-of-field monitoring) were selected for modeling based on prioritizing sites with long monitoring records and minimal gaps or noted anomalies, while also capturing a variety of crop rotations and soils conditions. APEX models were initially set up using as much site-specific information as was available, including SSURGO soils data, known agronomic operations, and a combination of known and generalized information on manure nutrient content and physical characteristic. Local meteorological data was also collected in association with monitoring of these sites and used for calibration and validation simulations.

The calibration and validation of APEX sought to identify a global parameterization of the model that minimized model prediction bias and minimized the magnitude in model error in annual total P load predictions over seven calibration sites. Secondarily, minimization of model predicted average annual flow bias and magnitude of the errors in annual flow were considered. These model performance metrics were then applied to an independent set of five validation sites to assess the robustness of the parameterization in simulating unmonitored sites. The calibration/validation process included the following stages: 1.) Initial model setup and parameterization, 2.) Manual model evaluation and calibration, 3.) Automatic calibration of global parameterization, 4.) Monte Carlo analysis of soils parameter uncertainty with global parameterization, 5.) Automatic calibration of site-specific parameterization, and 6.) Monte Carlo analysis of soils parameter uncertainty with site-specific parameterization.

The steps in the calibration process that focused on a global parameterization, i.e., a set of parameters that are applied to all sites, had the greatest relevance for implementation of APEX-based modeling to quantify P loads across broad areas of Vermont's agricultural landscape. The results of the global parameterization calibration using representative soils properties demonstrated that on average, APEX simulations of average annual total P load would be less than 37% above or below measured values, with two thirds of sites deviating by less than 25% above or below measured values. Furthermore, the model simulations had no systematic bias (over versus under predicting monitoring data), showing a positive/negative bias of less than 1% across all twelve sites. The associated Monte Carlo analysis of soils parameter demonstrated that uncertainty in best available soils datasets can account for the observed bias in APEX simulation results, and that selection of "best" soils parameters within the range of uncertainty will often lead to improvements in model performance. This finding suggests that APEX model simulations based on site-specific soil properties will likely have reduced bias in average annual P load predictions.

The benefits tied to the adoption of manure management technologies include the generation of new manure-based fertilizer products that are both storable and transportable, allowing for placement where and when the nutrients are needed, and for allowing the export of these products to agricultural land that traditionally has not benefited from dairy manure. Using the APEX models for five sites (three tile drained, one edge-of-field, and the Miner site) developed using the global parameterization and site-specific soils, a suite of scenarios was simulated to assess the implementation of manure management technologies and a selection of conservation practices. These APEX simulations demonstrated the potential reduction of P loads that could be obtained through combinations of two manure technologies (DAF and evaporation) and four conservation practices (no-till, cover cropping, manure injection, and no-till plus cover cropping).

The results simulation of 114 scenarios, covering a range of sites, and manure technologies, showed that both P loads from surface transport and tile drain transport can be reduced can be reduced with these practices and technologies. When P levels in the soil are close to optimal and manure-based nutrient inputs are not excessive, the benefits realized by the implementation of manure management technology ranged from a 6% increase to as much as a 13% decrease in total P loses, with a median decrease of 6%. For scenarios where soil P was high and manure applications were higher than crop demand, the benefits of manure technologies increased. Under these situations, the median total P load reduction was 15%, and as high as 30% in some scenarios. It was also found that this benefit was greater following a 10-year period after the initial adoption of manure technology, as a result of drawing down excessive P in the soil over time. In evaluating the second 10-year period after adoption of manure technologies, the APEX simulations suggested that median reductions in P loads of between 24% and 27% could be achieved, with some scenarios resulting in reductions in P loses of 40%. The modeling of technologies and practices focused only on phosphorus metrics due to its importance to water quality in the Lake Champlain Basin. However, the overall impact of technologies on other nutrients, such as nitrogen, was not part of this study but will likely provide additional incentive in support of manure technology adoption.

The project efforts described in this report addressed several research needs identified in the 2017 Vermont Subsurface Agricultural Tile Drainage Report, including quantification of phosphorous concentrations and loads in drain flow; comparison of phosphorus concentrations and loads in drain flow with surface runoff; evaluation of factors controlling phosphorus transmission in tile drainage and; evaluation of the effectiveness of management practices to reduce P loads in tile drain flows. Central to addressing all of these research needs described above was development of a modeling approach capable of simulating P transport due to runoff, erosion, and subsurface flow through tile drainage networks, as well as assessing the P load reduction benefits of manure management technologies and on-field conservation practices. The calibration and validation of the APEX model across twelves sites in the Lake Champlain Basin represents an important milestone in the development of a systematic and unbiased approach to quantifying P load across farmland throughout the basin. With a tool that has been shown to predict both surface P loads and tile drain P loads with reasonable accuracy across crop rotations and practices found within the Lake Champlain Basin, we can now focus more energy into integration of this modeling approach within a broader phosphorus protocol aimed at incentivizing farmers to adopt technologies and practices that lead to a water quality benefit. A basin-wide adoption of such an approach to quantifying the benefits of manure technologies and conservation practices, coupled with the opportunity for incentives, should ultimately lead us more directly towards a future where goals of the Lake Champlain P TMDL have been met.

Refinement of Critically Needed Assessment Tools for Tile Drainage Phosphorus Loading in the Lake Champlain Basin

Contents

Acknowledgements ....

Title and Approval Page i

Executive Summary ii

Contents iv

1. Project Introduction 1

2. Tasks Completed 4

2.1. Task 1: Compilation and Evaluation of Field-Level Monitoring Efforts 4

2.2. Task 2: Model Calibration and Validation with Monitoring Data 5

2.3. Task 3: Assessment of Management Scenarios for Innovative Manure Management 6

2.4. Task 4: Inform Existing Agency Efforts on Modeling Applications and Outcomes 7

2.5. Task 5: Project Reporting 7

3. Modeling Methodology and Results 8

3.1. Compilation and Evaluation of Field-Level Monitoring Efforts 8

3.1.1. Site Selection 8

3.1.2. Compilation and Evaluation of Data 14

3.2. Model Calibration and Validation with Monitoring Data 16

3.2.1. APEX Model Parameterization from Field Data 16

3.2.2. Extraction and Processing of Monitoring Data for Model Comparison 29

3.2.3. APEX Calibration and Validation 29

3.3. Assessment of Management Scenarios for Innovative Manure Management 41

3.3.1. Background 41

3.3.2. Modeling Approach 42

3.3.3. Results 45

3.4. Inform Existing Agency Efforts on Modeling Applications and Outcomes 60

4. Quality Assurance Tasks Completed 62

4.1. Identification of Monitoring Sites for Modeling 62

4.2. APEX Model Calibration/Validation 62

4.3. Parameterization of Manure Management Scenarios/Technologies 62

5. Deliverables Completed 63

5.1. Quality Assurance Project Plan 63

5.2. Quarterly Reports 63

5.3. Project Task Memos and Presentations 63

5.4. Final Report and Deliverables 63

6. Conclusions 64

7. References 66

8. Appendices 68

Appendix A: Time Series Plots of Annual Flow and Total P Based on Global Parameterization Simulations, Representative Soil Parameters ... 69
Appendix B: Time Series Plots of Annual Flow and Total P Based on Global Parameterization Simulations, Best Soils Parameters ... 82
Appendix C: Cumulative Distribution Plots of Model-Predicted Total P Percent Bias, Soils Monte Carlo Analysis with Global Parameterization. ... 95
Appendix D: Time Series Plots of Annual Flow and Total P Based on Site-Specific Parameterization Simulations, Representative Soils Parameters ... 102
Appendix E: Time Series Plots of Annual Flow and Total P Based on Site-Specific Parameterization Simulations, Best Soils Parameters ... 115
Appendix F: Tables and Bar Charts Showing Results of Manure Management Scenarios for Optimal P Soils ... 128
Appendix G: Tables and Bar Charts Showing Results of Manure Management Scenarios for High P Soils ... 139

List of Figures

Figure 1. The Newtrient ESM Concept. ... 2
Figure 2. Observed (blue) and model-predicted (orange) average annual total P loads, where predicted loads are based on the global parameter set and representative soils. ... 34
Figure 3. Observed versus model-predicted average annual total P for all 12 sites using global parameterization. ... 35
Figure 4. Observed (blue) and model-predicted (orange) average annual total P loads, where predicted loads are based on the global parameter set and "best" soils parameters. ... 37
Figure 5. Observed versus model-predicted average annual total P for all 12 sites using global parameterization with "best" soils parameters. ... 37
Figure 6. Observed (blue) and model-predicted (orange) average annual total P loads, where predicted loads are based on the site-specific parameter set and representative soils parameters. ... 39
Figure 7. Observed versus model-predicted average annual total P for all 12 sites using site-specific parameterization with representative soils parameters. ... 39
Figure 8. Observed (blue) and model-predicted (orange) average annual total P loads, where predicted loads are based on the site-specific parameter set and "best" soils parameters. ... 40
Figure 9. Observed versus model-predicted average annual total P for all 12 sites using site-specific parameterization with "best" soils parameters. ... 40
Figure 10. Median reduction in total P load by conservation practice from APEX simulation of Conservation Practices on fields with optimal P soils (including no technology, DAF, and evaporation technology scenarios). ... 48
Figure 11. Median reduction in total P load by manure technology resulting from APEX simulation of fields with optimal P soils. ... 50
Figure 12. Cumulative Distributions of Average Annual Total P Load Reductions Resulting from Manure Technologies over First Ten-Year and Second Ten-Year Periods ... 52
Figure 13. Median reduction in total P load by conservation practice from APEX simulation of conservation practices on fields with high P soils (including no technology, DAF, and evaporation technology scenarios). ... 55
Figure 14. Median reduction in total P load by manure technology resulting from APEX simulations of fields with high P soils. ... 57
Figure 15. Cumulative Distributions of Average Annual Total P Load Reductions Resulting from Manure Technologies over First Ten-Year and Second Ten-Year Periods ... 58
Figure 16. P Applied from Manure Products from Evaporation Technology and Total P in Plow Layer Under No-till Conservation Practices for Site M1, High Soil P Scenario. ... 60
Figure 17. P Applied from Manure Products from Evaporation Technology and Total P in Plow Layer Under No-till Conservation Practices for Site JBT18, High Soil P Scenario. ... 60
Figure 18. Observed versus model-predicted annual surface runoff (flow) at CHA1. ... 69
Figure 19. Observed versus model-predicted annual total P at CHA1. ... 69
Figure 20. Observed versus model-predicted annual surface runoff (flow) at FER1. ... 70
Figure 21. Observed versus model-predicted annual total P at FER1. ... 70
Figure 22. Observed versus model-predicted annual tile flow at JBT01. ... 71
Figure 23. Observed versus model-predicted annual total P at JBT01. ... 71

Figure 24. Observed versus model-predicted annual tile flow at JBT04. 72
Figure 25. Observed versus model-predicted annual total P at JBT04. 72
Figure 26. Observed versus model-predicted annual t tile flow at JBT05. 73
Figure 27. Observed versus model-predicted annual total P at JBT05. 73
Figure 28. Observed versus model-predicted annual tile flow at JBT07. 74
Figure 29. Observed versus model-predicted annual total P at JBT07. 74
Figure 30. Observed versus model-predicted annual tile flow at JBT11. 75
Figure 31. Observed versus model-predicted annual total P at JBT11. 75
Figure 32. Observed versus model-predicted annual tile flow at JBT18. 76
Figure 33. Observed versus model-predicted annual total P at JBT18. 76
Figure 34. Observed versus model-predicted annual surface runoff (flow) at PAW1. 77
Figure 35. Observed versus model-predicted annual total P at PAW1. 77
Figure 36. Observed versus model-predicted annual surface runoff (flow) at SHE1......................... 78
Figure 37. Observed versus model-predicted annual total P at SHE1. 78
Figure 38. Observed versus model-predicted annual surface runoff (flow) at SHO1. 79
Figure 39. Observed versus model-predicted annual total P at SHO1. 79
Figure 40. Observed versus model-predicted annual tile flow at M1. 80
Figure 41. Observed versus model-predicted annual total P in tile flow at M1. 80
Figure 42. Observed versus model-predicted annual surface runoff (flow) at M1. 81
Figure 43. Observed versus model-predicted annual total P in surface runoff at M1....................... 81
Figure 44. Observed versus model-predicted annual surface runoff (flow) at CHA1. 82
Figure 45 Observed versus model-predicted annual total P at CHA1. 82
Figure 46. Observed versus model-predicted annual surface runoff (flow) at FER1. 83
Figure 47. Observed versus model-predicted annual total P at FER1. 83
Figure 48. Observed versus model-predicted annual tile flow at JBT01. 84
Figure 49. Observed versus model-predicted annual total P at JBT01. 84
Figure 50. Observed versus model-predicted annual tile flow at JBT04. 85
Figure 51. Observed versus model-predicted annual total P at JBT04. 85
Figure 52. Observed versus model-predicted annual tile flow at JBT05. 86
Figure 53. Observed versus model-predicted annual total P at JBT05. 86
Figure 54. Observed versus model-predicted annual tile flow at JBT07. 87
Figure 55. Observed versus model-predicted annual total P at JBT07. 87
Figure 56. Observed versus model-predicted annual tile flow at JBT11. 88
Figure 57. Observed versus model-predicted annual total P at JBT11. 88
Figure 58. Observed versus model-predicted annual tile flow at JBT18. 89
Figure 59. Observed versus model-predicted annual total P at JBT18. 89
Figure 60. Observed versus model-predicted annual surface runoff (flow) at PAW1. 90
Figure 61. Observed versus model-predicted annual total P at PAW1. 90
Figure 62. Observed versus model-predicted annual surface runoff (flow) at SHE1......................... 91
Figure 63. Observed versus model-predicted annual total P at SHE1. 91
Figure 64. Observed versus model-predicted annual surface runoff (flow) at SHO1. 92
Figure 65. Observed versus model-predicted annual total P at SHO1. 92
Figure 66. Observed versus model-predicted annual tile flow at M1. 93
Figure 67. Observed versus model-predicted annual total P in tile flow at M1. 93
Figure 68. Observed versus model-predicted annual surface runoff (flow) at M1. 94
Figure 69. Observed versus model-predicted annual total P in surface runoff at M1....................... 94
Figure 70. Cumulative distribution of average annual total P percent bias for CHA1. 95
Figure 71. Cumulative distribution of total P percent bias for FER1. 95
Figure 72. Cumulative distribution of total P percent bias for JBT01. 96
Figure 73. Cumulative distribution of total P percent bias for JBT04. 96
Figure 74. Cumulative distribution of total P percent bias for JBT05. 97
Figure 75. Cumulative distribution of total P percent bias for JBT07. 97
Figure 76. Cumulative distribution of total P percent bias for JBT11. 98
Figure 77. Cumulative distribution of total P percent bias for JBT18. 98
Figure 78. Cumulative distribution of total P percent bias for PAW1. 99
Figure 79. Cumulative distribution of total P percent bias for SHE1. 99
Figure 80. Cumulative distribution of total P percent bias for SHO1.. 100
Figure 81. Cumulative distribution of total P percent bias for M1 tile. 100
Figure 82. Cumulative distribution of total P percent bias for M1 surface runoff. 101
Figure 83. Observed versus model-predicted annual surface runoff (flow) at CHA1. 102
Figure 84. Observed versus model-predicted annual total P at CHA1. 102
Figure 85. Observed versus model-predicted annual surface runoff (flow) at FER1. 103

Figure 86. Observed versus model-predicted annual total P at FER1. 103
Figure 87. Observed versus model-predicted annual tile flow at JBT01. 104
Figure 88. Observed versus model-predicted annual total P at JBT01. 104
Figure 89. Observed versus model-predicted annual tile flow at JBT04. 105
Figure 90. Observed versus model-predicted annual total P at JBT04. 105
Figure 91. Observed versus model-predicted annual tile flow at JBT05. 106
Figure 92. Observed versus model-predicted annual total P at JBT05. 106
Figure 93. Observed versus model-predicted annual tile flow at JBT07. 107
Figure 94. Observed versus model-predicted annual total P at JBT07. 107
Figure 95. Observed versus model-predicted annual tile flow at JBT11. 108
Figure 96. Observed versus model-predicted annual total P at JBT11. 108
Figure 97. Observed versus model-predicted annual tile flow at JBT18. 109
Figure 98. Observed versus model-predicted annual total P at JBT18. 109
Figure 99. Observed versus model-predicted annual surface runoff (flow) at PAW1. 110
Figure 100. Observed versus model-predicted annual total P at PAW1. 110
Figure 101. Observed versus model-predicted annual surface runoff (flow) at SHE1..................... 111
Figure 102. Observed versus model-predicted annual total P at SHE1. 111
Figure 103. Observed versus model-predicted annual surface runoff (flow) at SHO1. 112
Figure 104. Observed versus model-predicted annual total P at SHO1. 112
Figure 105. Observed versus model-predicted annual tile flow at M1. 113
Figure 106. Observed versus model-predicted annual total P in tile drainage at M1. 113
Figure 107. Observed versus model-predicted annual surface runoff (flow) at M1. 114
Figure 108. Observed versus model-predicted annual total P in surface runoff at M1................... 114
Figure 109. Observed versus model-predicted annual surface runoff (flow) at CHA1. 115
Figure 110. Observed versus model-predicted annual total P at CHA1. 115
Figure 111. Observed versus model-predicted annual surface runoff (flow) at FER1. 116
Figure 112. Observed versus model-predicted annual total P at FER1. 116
Figure 113. Observed versus model-predicted annual tile flow at JBT01. 117
Figure 114. Observed versus model-predicted annual total P at JBT01. 117
Figure 115. Observed versus model-predicted annual tile flow at JBT04. 118
Figure 116. Observed versus model-predicted annual total P at JBT04. 118
Figure 117. Observed versus model-predicted annual tile flow at JBT05. 119
Figure 118. Observed versus model-predicted annual total P at JBT05. 119
Figure 119. Observed versus model-predicted annual tile flow at JBT07. 120
Figure 120. Observed versus model-predicted annual total P at JBT07. 120
Figure 121. Observed versus model-predicted annual tile flow at JBT11. 121
Figure 122. Observed versus model-predicted annual total P at JBT11. 121
Figure 123. Observed versus model-predicted annual surface runoff (flow) at JBT18.................... 122
Figure 124. Observed versus model-predicted annual total P at JBT18. 122
Figure 125. Observed versus model-predicted annual tile flow at PAW1....................................... 123
Figure 126. Observed versus model-predicted annual total P at PAW1. 123
Figure 127. Observed versus model-predicted annual surface runoff (flow) at SHE1..................... 124
Figure 128. Observed versus model-predicted annual total P at SHE1. 124
Figure 129. Observed versus model-predicted annual surface runoff (flow) at SHO1. 125
Figure 130. Observed versus model-predicted annual total P at SHO1. 125
Figure 131. Observed versus model-predicted annual tile flow at M1. 126
Figure 132. Observed versus model-predicted annual total P in tile drainage at M1. 126
Figure 133. Observed versus model-predicted annual surface runoff (flow) at M1. 127
Figure 134. Observed versus model-predicted annual total P in surface runoff at M1................... 127
Figure 135. Annual average tile P loads for JBT01 with optimal P soils, based on combinations of manure management technology and conservation practices. 131
Figure 136. Annual average surface runoff soluble P loads for JBT01 with optimal P soils, based on combinations of manure management technology and conservation practices. 131
Figure 137. Annual average surface runoff sediment P loads for JBT01 with optimal P soils, based on combinations of manure management technology and conservation practices. 132
Figure 138. Annual average tile P loads for JBT11 with optimal soils, based on combinations of manure management technology and conservation practices. No-till, cover crop, and combined no-till and cover crop options were not simulated for JBT11 (permanent hay). 132
Figure 139. Annual average surface runoff soluble P loads for JBT11 with optimal P soils, based on combinations of manure management technology and conservation practices. No-till, cover crop, and combined no-till and cover crop options were not simulated for JBT11 (permanent hay)...... 133

Figure 140. Annual average surface runoff sediment P loads for JBT11 with optimal P soils, based on combinations of manure management technology and conservation practices . No-till, cover crop, and combined no-till and cover crop options were not simulated for JBT11 (permanent hay). 134
Figure 141. Annual average tile P loads for JBT18 with optimal P soils, based on combinations of manure management technology and conservation practices. 135
Figure 142. Annual average surface runoff soluble P loads for JBT18 with optimal P soils, based on combinations of manure management technology and conservation practices. 135
Figure 143. Annual average surface runoff sediment P loads for JBT18 with optimal P soils, based on combinations of manure management technology and conservation practices. 136
Figure 144. Annual average tile P loads for M1 with optimal P soils, based on combinations of manure management technology and conservation practices. 136
Figure 145. Average annual surface runoff soluble P loads for M1 with optimal P soils, based on combinations of manure management technology and conservation practices 137
Figure 146. Annual average surface runoff sediment P loads for M1 with optimal P soils, based on combinations of manure management technology and conservation practices. 137
Figure 147. Average annual surface runoff soluble P loads for PAW1 with optimal P soils, based on combinations of manure management technology and conservation practices. 138
Figure 148. Annual average surface runoff sediment P loads for PAW1 with optimal P soils, based on combinations of manure management technology and conservation practices. 138
Figure 149. Annual average tile P loads for JBT01 with high P soils, based on combinations of manure management technology and conservation practices. 142
Figure 150. Annual average surface runoff soluble P loads for JBT01 with high P soils, based on combinations of manure management technology and conservation practices. 142
Figure 151. Annual average surface runoff sediment P loads for JBT01 with high P soils, based on combinations of manure management technology and conservation practices. 143
Figure 152. Annual average tile P loads for JBT11 with high P soils, based on combinations of manure management technology and conservation practices. No-till, cover crop, and combined no-till and cover crop options were not simulated for JBT11 (permanent hay). 143
Figure 153. Annual average surface runoff soluble P loads for JBT11 with high P soils, based on combinations of manure management technology and conservation practices. No-till, cover crop, and combined no-till and cover crop options were not simulated for JBT11 (permanent hay). 144
Figure 154. Annual average surface runoff sediment P loads for JBT11 with high P soils, based on combinations of manure management technology and conservation practices. No-till, cover crop, and combined no-till and cover crop options were not simulated for JBT11 (permanent hay). 145
Figure 155. Annual average tile P loads for JBT18 with high P soils, based on combinations of manure management technology and conservation practices. 146
Figure 156. Annual average surface runoff soluble P loads for JBT18 with high P soils, based on combinations of manure management technology and conservation practices. 146
Figure 157. Annual average surface runoff sediment P for JBT18 with high P soils, based on combinations of manure management technology and conservation practices. 147
Figure 158. Annual average tile P loads for M1 with high P soils, based on combinations of manure management technology and conservation practices. 147
Figure 159. Annual average surface runoff soluble P loads for M1 with high P soils, based on combinations of manure management technology and conservation practices. 148
Figure 160. Annual average surface runoff sediment P loads for M1 with high P soils, based on combinations of manure management technology and conservation practices. 148
Figure 161. Annual average surface runoff soluble P loads for PAW1 with high P soils, based on combinations of manure management technology and conservation practices. 149
Figure 162. Annual average surface runoff sediment P loads for PAW1 with high P soils, based on combinations of manure management technology and conservation practices. 149

Table of Tables

Table 1. Metadata on Stone monitored tile drained sites in the Vermont portion of the Lake Champlain Basin. 12
Table 2. Metadata on Stone monitored edge-of-field sites in the Vermont portion of the Lake Champlain Basin. 13
Table 3. Meteorological data gaps. 15

Table 4. Soil and tile drainage parameters (by soil layer where applicable) used in initial parameterization of APEX models. 19
Table 5. Management operations for APEX model of JBT01. 21
Table 6. Management operations for APEX model of JBT04. 21
Table 7. Management operations for APEX model of JBT05. 21
Table 8. Management operations for APEX model for JBT07. 22
Table 9. Management operations for APEX model of JBT11. 22
Table 10. Management operations for APEX model of JBT18. 22
Table 11. Management operations for APEX model of CHA1. 23
Table 12. Management operations for APEX model of FER1 23
Table 13. Management operations for APEX model of PAW1 24
Table 14. Management operations for APEX model of SHE1. 24
Table 15. Management operations for APEX model of SHO1. 25
Table 16. Management operations for APEX model of Miner site. 26
Table 17. Nutrient fractions in manure and fertilizers used in APEX models for calibration/validation. 28
Table 18. APEX parameters considered in automatic calibration. 30
Table 19. Summary of calibrated APEX parameter values for the global parameter calibration. 32
Table 20. Summary of calibration statistics for calibration sites, validation sites, and all sites. 33
Table 21. Summary of individual site calibration statistics, global parameterization. 33
Table 22. Summary of individual site calibration statistics, global parameterization with "best" soils parameters. 36
Table 23. Confidence intervals of total P percent bias from global parameterization soils uncertainty Monte Carlo analysis. 38
Table 24. Description of scenarios conducted for assessment of manure management. 43
Table 25. Nutrient fractions for dissolved air floatation (DAF) and evaporation manure products. 44
Table 26. Range of percent P reductions in manure management scenarios resulting from APEX simulation of conservation practices on fields with optimal P soils (including no technology, dissolved air floatation (DAF), and evaporation technology scenarios). 47
Table 27. Range of P loads in manure management scenarios resulting from APEX simulation of conservation practices on fields with optimal P soils and (including no technology, dissolved air floatation (DAF), and evaporation technology scenarios). 47
Table 28. Range in percent P reductions in manure management scenarios resulting from APEX simulation of manure technologies on fields with optimal P soils. 49
Table 29. Range in P loads in manure management scenarios resulting from APEX simulation of manure technologies on fields with optimal P soils. 49
Table 30. Reductions in total P load resulting from manure technology by time for selected sites and practices resulting from APEX simulation of fields with optimal P soils. 51
Table 31. Range in percent P reductions in manure management scenarios resulting from APEX simulation of conservation practices on fields with high P soils (including no technology, dissolved air floatation (DAF), and evaporation technology scenarios). 54
Table 32. Range in P loads in manure management scenarios resulting from APEX simulation of conservation practices on fields with high P soils (including no technology, dissolved air floatation (DAF), and evaporation technology scenarios). 54
Table 33. Range in percent P reductions in manure management resulting from APEX simulation of manure technologies on fields with high P soils . 56
Table 34. Range in P loads in manure management scenarios resulting from APEX simulation of manure technologies on fields with high P soils. 56
Table 35. Reductions in total P load resulting from manure technology by time for selected sites and practices, high soil P simulations. 58
Table 36. Annual average tile P loads from manure management scenarios, optimal P soils. 128
Table 37. Annual average surface runoff soluble P loads from manure management scenarios, optimal P soils. 128
Table 38. Annual average surface runoff sediment P loads from manure management scenarios, optimal P soils. 129
Table 39. Annual average total P loads from manure management scenarios, optimal P soils. 129
Table 40. Annual average mineral P applied to field in manure management scenarios, optimal P soils. 130
Table 41. Annual average tile P loads from manure management scenarios, high P soils. 139
Table 42. Annual average surface runoff soluble P loads from manure management scenarios, high P soils. 139

Table 43. Annual average surface runoff sediment P loads from manure management scenarios, high P soils. 140
Table 44. Annual average total P loads from manure management scenarios, high P soils. 140
Table 45. Annual average mineral P applied to field in manure management scenarios, high P soils. 141

1. Project Introduction

The contribution of phosphorus (P) from the agricultural tile drains in the Lake Champlain Basin is considered substantial, yet not quantified or even coarsely estimated in current P budgets, particularly in Vermont's phosphorus TMDL. This project sought to fill a very important, specific and stand-alone knowledge gap related to edge-of-field losses (both overland and tile drain) using existing data to calibrate and validate field-level models using Agricultural Policy Environmental eXtender (APEX) Version 1501 (Steglich et al., 2016). The focus was on calibrating and validating APEX using existing monitoring data in the basin for surface and subsurface field contributions. This work has state, regional and national implications for addressing the nebulous and poorly understood contributions of P in tile drainage and its management and provides an essential tool for reducing phosphorus to the Lake Champlain Basin.

Newtrient is a private company that was formed in 2015 by 12 leading dairy cooperatives (including Agri-Mark and DFA) as well as Dairy Management, Inc. and the National Milk Producers Federation. Newtrient was created to address some of the most challenging environmental issues facing the industry with the overarching goal of reducing dairy's environmental footprint.

Vermont was one of the first states where Newtrient placed resources and effort due to the water quality challenges in the Lake Champlain Basin coupled with the environmental impact of dairy. Newtrient's approach has been centered around the development of a market-based mechanism (as one tool) to drive water quality improvement in the Lake Champlain Basin called an Environmental Services Marketplace ("ESM"). The ESM seeks to optimize resources to enhance environmental benefit with verified and certified low-cost reductions (e.g., dairy farms employing practices and/or technologies) to ensure known regulatory outcomes (Figure 1). The result is water quality improvement, reduced taxpayer burden and the economic certainty necessary to drive the adoption of farm-based sustainable practices and technologies.

Newtrient was awarded a Vermont Clean Water Grant (administered through the Agency of Agriculture, Food and Markets, $160,000) in 2017 that included the development of a phosphorus protocol for translating farm practice to water quality benefit. The protocol, which will use an APEX-based model, is the math behind quantifying the impact of practice or technology adoption on phosphorus load to the basin. In addition, Newtrient was awarded a USDA cooperative agreement ($370,000) to further augment and test the protocol and develop a structure for a clearinghouse. Considered in aggregate, the protocol and clearinghouse form the underpinnings of the ESM (Figure 1).

Figure 1. The Newtrient ESM Concept.

In order to achieve the Lake Champlain Basin Program's commitment to improving the environmental, social, and cultural resources in the LCB, significant objectives relating to the transmission of phosphorus to LCB surface waters that must be addressed include: 1) reducing the knowledge gap of site-specific variables and efficiency of conservation practices that affect phosphorus loading from surface runoff and subsurface tile drainage attributed to the implementation of Required Agricultural Practices (the VT RAPs), 2) creating a driving force for adoption of traditional and innovative agricultural conservation practices and technologies to generate quantified, verified phosphorus loading reductions, and 3) implementing a long-term, basin-wide phosphorus reduction strategy that optimizes phosphorus management on-farm, reduces import into the basin and provides economically viable means of export (potentially out of basin).

The model calibration and validation conducted in this effort will be incorporated into a protocol with the necessary scientific rigor to withstand scrutiny and support Newtrient's broader mission of creating an ESM in the Lake Champlain Basin to drive water quality improvement. Though the ESM is currently being examined in the VT portion of Lake Champlain, we believe this can and will eventually serve to facilitate phosphorus reductions from agriculture in the entire basin. The protocol seeks to:

1. Quantify the effect of innovative manure management technologies and other conservation practices on surface runoff and subsurface tile drainage phosphorus loading reductions to Lake Champlain.

2. Verify the effects of management options on subsurface tile drainage phosphorus loading. The development of a mechanistic model calibrated to farm operations with subsurface tile drainage in the LCB will provide crucial knowledge to support the Tile Drain Advisory Group's assessment of management options for tile drain management and recommendations for implementation.

3. Identify improved performance opportunities for dairy operators basin-wide that meet and exceed the Lake Champlain TMDL goals and Vermont's Required Agricultural Practices.

4. Generate the environmental certainty required to make basin-wide adoption of manure management technologies and other conservation practices economically feasible for agricultural operators. The accurate quantification of phosphorus loading reductions generated by manure management technologies and conservation practices provides the environmental certainty required to allow innovative market based approaches, such as the ESM, to transform water quality benefits associated with manure management technologies and other conservation practices into a form of revenue and significantly aid in the basin-wide adoption of these technologies and practices.

5. Create the foundation for phosphorus accounting for the Lake Champlain Basin. This is an especially pivotal component for reducing the long-term mass phosphorus balance for the Lake Champlain Basin. The ability to utilize the ESM (Protocol and Clearinghouse) will not only foster the adoption of manure management technologies that reclaim phosphorus, but enable the basis for phosphorous accounting for the entire LCB that can be utilized to promote a circular economy through incentivizing the purchase of reclaimed phosphorus from the basin and disincentivizing the use of imported phosphorous.

The Lake Champlain Basin has been a top priority for Newtrient since 2015. Newtrient is committed to developing an ESM using a phosphorus protocol for translating farm practice to water quality benefit and facilitating through a clearinghouse to advance water quality in the Lake Champlain Basin. To this end, we continue to make substantial investment through Newtrient's internal resources augmented with existing grant programs (Vermont Clean Water Fund and a USDA Cooperative Agreement) focused on advancing the ESM.

The overarching goal of this project was to develop, calibrate and validate a robust APEX-based model capable of representing edge-of-field P loads and use the proven model to investigate scenarios for innovative manure management and on-field conservation practices. This larger goal was accomplished by focusing on two primary objectives:

1. The first objective of this project was to calibrate and validate an APEX-based model using existing monitoring data of surface runoff and tile drained sites throughout the Lake Champlain basin. This addresses multiple research needs, including quantification of P loads from tile drain flow under various conditions, comparison of P load from tile flow and surface runoff, and evaluation of factors influencing P movement in tile drainage.

2. The second objective was to quantitatively evaluate the effectiveness of innovative manure management and on-field conservation practice scenarios (such as separation of manure liquid from manure solids) using the calibrated model.

This project applied APEX with some customizations, to adequately address P loads via tile drainage. This report describes the calibration/validation approach and results, as well as summarizes the parameterization of and results associated with evaluating manure management scenarios or technologies.

2. Tasks Completed

The tasks completed in this project closely followed the approved project workplan. These tasks are described in this section.

2.1. Task 1: Compilation and Evaluation of Field-Level Monitoring Efforts

The first task of this project had two components. The first component was to develop a secondary data Quality Assurance Project Plan (QAPP). This task was completed, and the plan followed throughout the course of the project. The plan focused on review of existing datasets compiled for parameterization of APEX models for field sites, following a process for calibration and validation of the APEX models, review and checking of APEX model inputs and results of the calibration and validation process, and review of model inputs and results of manure technology and conservation practice modeling.

The second component under this task focused on compiling and evaluating currently available field-level monitoring data in both the Vermont and New York portions of the Lake Champlain Basin (LCB). Stone Environmental considered past and ongoing monitoring efforts and datasets that could provide value in better parameterizing and validating the APEX model for conditions on LCB farms.

Stone has led edge-of-field monitoring studies at 16 sites (eight paired watersheds) on the Vermont side of the lake since 2012, each having collected between two and five years of data (Braun et al., 2016; Braun and Meals, 2019). Six of these sites continue to be monitored. The paired watershed design allows for examination of the effects of varying agronomic practices on observed water quantity and quality. In addition, in 2017, Stone began monitoring flow and nutrients in 13 tile drained sites within the St. Albans Bay watershed (Braun et al., 2019). The 13 tile drained sites represent a variety of crops, including soybean, silage corn, alfalfa hay, clover hay, and a strip-cropped hay/corn site. While these 29 sites represent a large portion of the available edge-of-field and tile monitoring data within the LCB, Stone is aware that other groups, including the University of Vermont, and the Miner Institute in New York state, that have ongoing or planned monitoring efforts. As such, metadata on the range of these sites was compiled and summarized to help inform the selection of appropriate sites for model applications.

The most important data elements required for a site to be a strong candidate for modeling included high frequency flow and nutrient concentration data, on-site or very near-site daily meteorological data, field conditions prior to monitoring (soil P, residue/vegetation cover), thorough documentation of field agronomic operations, nutrient/fertilizer application rates, manure nutrient contents, soil characteristics, and in the case of tile drained sites, characteristics of the tile network (e.g., pattern/spacing). Stone reviewed all the candidate sites and preferentially selected those with the most complete datasets in formats that could most readily be used in modeling. In addition, the person responsible for each monitoring study was consulted to better understand any challenges/limitations associated with the data at each site. For sites monitored by Stone, this involved coordination with Dave Braun (water quality monitoring program lead at Stone) for guidance in identifying sites with the highest quality data.

Evaluation of the APEX model over a range of field conditions was important in gaining broader confidence in the model's predictive capability. From the subset of sites determined to have sufficiently robust datasets, five edge-of-field and seven tile drained sites were chosen to include in the APEX model evaluation. A balance of corn silage and hay sites, the two dominant crops within the LCB, were chosen with preference given to sites with longer monitoring records in addition to the data elements previously described. Confidentiality agreements established with producers that are accommodating current monitoring efforts were honored for modeling efforts.

Monitoring sites that were considered and the criteria for selecting sites and the final recommended set of sites to include in the model calibration and validation task and subsequent tasks are described in Section 3.1.

2.2. Task 2: Model Calibration and Validation with Monitoring Data

Activities under Task 2 focused on calibration and validation of the APEX model with monitoring data of surface runoff and tile drained sites throughout the Lake Champlain basin. These efforts provide a strong foundation for a quantitative approach for calculating P load reductions on farms resulting from practice implementation and innovative nutrient management technologies. The focus of this task was a well-documented calibration and validation of the APEX model covering multiple field conditions and agronomic practices based on both surface and subsurface P monitoring data.

The population of 12 sites selected for this analysis were separated into a group of sites for calibration and a group of sites for validation. This approach is an alternative to splitting the observed data record for each site into a calibration and validation period. As anticipated, many of the selected sites (particularly the tile drained sites) had a short record of 2 years or less, and a longer calibration period on fewer sites was preferable to shorter calibration period on all sites. In addition, an important objective of this task was to achieve predictive model capabilities that can generate estimates of P loads and load reductions resulting from practices at un-monitored/un-calibrated sites, inclusive of tile and surface transport. Three of the five surface edge-of-field monitoring sites were used as calibration sites and the other two as validation sites. For the tile monitoring sites, four of the seven sites were calibration sites with the other three serving as validation sites.

All available site-specific data for each of the monitoring sites was compiled and used to establish the initial parameterization of the APEX model at each site. The agronomic operations of the field for the years monitored and the soil conditions was critical. Field agronomic operations had already been compiled for many of the surface edge-of-field monitoring sites, and coordination with farmers allowed for compilation of records at the tile monitoring sites. When field-specific soil physical parameters were not available, the NRCS SSURGO database was used to identify the dominant soil properties required by APEX. Site-specific meteorological stations were available during the monitoring period for most sites, and missing data or data preceding the beginning of monitoring was obtained from nearby NCDC/COOP stations.

The calibration effort included a deterministic component where model-predicted and observed flow and P load was evaluated at an annual time step. Hydrologic model calibration goodness-of-fit statistics including the Percent Bias, Absolute Value of Percent Bias, and Mean Absolute Error were applied at each calibration and validation site to evaluate the APEX model performance. An important aspect of the calibration approach was identifying a "global" parameter set that provides satisfactory simulations at all sites. Achieving a calibration with high performance based on independent site-specific calibrations does not provide as high a value as a single calibration/parameter set that can be more broadly applied with confidence to a broader region, such as the Lake Champlain Basin. Establishment of a global calibration capable of simulating both surface and tile fluxes across a range of sites was a primary goal of this task.

During the deterministic calibration effort, performance of the current algorithms used by APEX to simulate tile flow and tile P transport were evaluated. No major deficiencies were identified based on examination of the methods and model calibration performance; therefore, no algorithms were modified for Task 2 of this work, where model calibration and validation were performed.

In addition to the deterministic calibration and validation exercise, a Monte Carlo analysis was conducted to evaluate the variability in model predictions based upon the uncertainty in key parameter value assumptions. The focus of the Monte Carlo analysis conducted was on soil parameters obtained from the SSURGO soils database. These parameters are provided with value ranges, thus have a defined level of uncertainty. One result of the Monte Carlo analysis was a cumulative probability distribution of predicted P load from each site. A comparison of the observed P load (e.g., mean annual) with the cumulative probability distribution from the APEX model simulations provided another valuable metric to assess the model's predictive ability and reliability. Furthermore, evaluation of the Monte Carlo simulation approach will help guide the methods adopted for accounting for uncertainty in P reduction predictions in the development of the P protocol. Finally, site-specific model calibrations were performed to evaluate the APEX model performance capabilities when parameterized for simulation of individual sites.

Model development, calibration, and validation is described in Section 3.2.

2.3. Task 3: Assessment of Management Scenarios for Innovative Manure Management

One of the benefits associated with a well-calibrated and validated hydrologic/water quality model is the ability to assess alternative management approaches on environmental quality. Several manure management approaches and technologies are currently under consideration across Vermont and the broader LCB. These technologies, including the separation of manure liquid from manure solids, have the potential to improve the form of nutrient content, timing, and quantity of the manure applied to agricultural fields throughout the basin with potentially important benefits to water quality through reduced potential for P loads. To meet Task 3, the project team explored a suite of manure management strategies in current practice and under consideration across the basin. Five of the calibrated field site APEX models were selected for evaluation of these technologies and additional on-field conservation practices.

The selection of manure management technologies for evaluation was based on those that are currently the most promising and relevant ones for farm operations within the LCB. Once these technologies were identified, APEX scenarios and simulations were developed for each of them at five of the calibrated field sites. The average annual total P loads in surface and tile transport were compared between pre-treatment conditions and post-treatment conditions for each technology. This comparison will be based on 1, 5 and 10-year timescales to observe the benefits of short, mid and long-term adoption of the new practices and allowing for a variety of weather conditions.

Background on the manure and/or field management technologies evaluated, how these practices were reflected in the APEX model parameterization, and the results of the pre- and post-treatment model simulation comparisons are presented in Section 3.3.

For assessing management scenarios that included innovative manure technologies, an additional capability was added to the APEX model by the Texas A&M model development team to simulate dynamic fertilizer/manure application based on P content of the soil at the end of each year in a simulation. This allowed for evaluation of the scenario in which due to improved storability and transportability of manure products resulting from implementation of a manure technology, these products could be stored until soil P levels required additional P to meet crop demands (and not necessarily applied every year).

2.4. Task 4: Inform Existing Agency Efforts on Modeling Applications and Outcomes

Task 4 of this project called for attending and presenting at two Tile Drain Advisory Group (TDAG) meetings during the project. One of the objectives of this project was to directly address several research needs identified in the 2017 Vermont Subsurface Agricultural Tile Drainage Report (i.e., quantification of phosphorous concentrations and loads in drain flow; comparison of phosphorus concentrations and loads in drain flow with surface runoff; evaluation of factors controlling phosphorus transmission in tile drainage and; evaluation of the effectiveness of management practices to reduce phosphorus loads in tile drain flows). A Tile Drain Advisory Group meeting was not been held until late in 2019, so in lieu of presenting at a meeting early in the year, the grant workplan and completed task 1 documents were sent to Laura DiPietro on July 2, 2019 with a request for feedback from the Tile Drain Advisory Group. Subsequently, select project team members participated in a meeting with the Tile Drain Advisory Group (TDAG) on December 20th, 2019 to share the outcomes from tasks 1 and 2 and the proposed approach for task 3 of the project. The feedback provided by the TDAG resulted in a modest revision to the APEX model calibration and validation methodology and discussion, which is reflected in this Final Report.

2.5. Task 5: Project Reporting

For this final project task, Newtrient prepared five Quarterly Progress Reports providing required information, and this document which represents the Final Project Report and documents efforts and findings of this project.

3. Modeling Methodology and Results

3.1. Compilation and Evaluation of Field-Level Monitoring Efforts

3.1.1. Site Selection

The most critical requirement for monitoring data for use in APEX model calibration and validation is an accurate determination of phosphorus loads on a seasonal and/or annual basis. This necessitates continuous monitoring of flow and frequent sampling of nutrient concentrations. The most comprehensive dataset available that meets these requirements has been collected by Stone Environmental, Inc. as part of multiple projects with several partners, including the LCBP, NRCS, and VAAFM. This dataset includes 16 edge-of-field sites (since 2013) and 12 tile drained sites (since 2017). A second dataset, collected and maintained by Miner Institute in northern NY, includes a site which has both edge-of-field and tile drainage monitoring with 3.5 years of available data. Additional monitoring data have been collected across the State of Vermont by the University of Vermont (UVM) Extension. These data consist primarily of phosphorus concentration only and do not include the continuous flow estimates required to calculate phosphorus loads. There are, however, two sites being monitored by UVM located in the southern Champlain valley (Panton) with one year of continuous flow monitoring along with P concentration measurements. The limitation of these two sites is that the flow data from multiple peak flow events was missing at the time of this study, making accurate estimation of annual loads for these sites difficult. Therefore, the most appropriate datasets for APEX model calibration and validation were the Stone datasets from sites located in Vermont and the combined tile and edge-of-field dataset collected by the Miner Institute and located in Chazy, New York.

Metadata related to the quality and quantity of data available for these sites were compiled and reviewed with the goal of identifying sites with the most complete and comprehensive datasets. We also strived to incorporate a variety of crops and field conditions where possible. In general, sites with longer monitoring records were prioritized, as well as sites that had minimal data gaps. Table 1 and

Table 2 were compiled for tile and edge-of-field monitoring sites, respectively, with input from Dave Braun (water quality monitoring program lead at Stone), to summarize available data with respect to critical elements identified in the workplan.

A total of 12 tile drained sites have been monitored by Stone between 2017 and present. For all of these, similar information on prior conditions, agronomic practices, nutrient/fertilizer inputs, and tile drain characteristics were available. No on-site soil data was collected, and the phosphorus contents of applied manure are unknown for all tile drained sites. These elements were therefore not significant factors in site selection and are not presented in Table 1. The frequency and resolution of flow and nutrient monitoring were also largely similar for these sites. In the case of tile drained sites, fields with surface inlets or diversions were also eliminated. The result of this selection process was that tile drained sites JBT01, JBT04, JBT05, JBT07, JBT11, and JBT18 were chosen for model application and subsequent tasks (Table 1). These sites were located in the Jewett Brook watershed in the Towns of St. Albans and Swanton. Of the selected sites, four of the seven have two years of monitoring data available. The sites include four permanent corn fields, one soybean field, one permanent alfalfa field, and one field in a corn/hay rotation.

A total of 16 edge-of-field monitoring sites have been monitored by Stone between 2013 and present. As with the tile drained sites, similar information on prior conditions, agronomic practices, and nutrient/fertilizer inputs are available for all these sites. For all edge-of-field sites, a one-time composite soil sample was obtained at the beginning of the monitoring period and is available for characterizing on-site soil, and no information is available for applied manure nutrient contents. The availability of these data elements did not vary across the sites, and therefore were not significant elements in the site selection and not presented in

Table 2. Again, the frequency and resolution of flow and nutrient monitoring were largely similar for these edge-of-field sites. Because more edge-of-field sites with longer-term records were available than tile drained sites, more consideration was placed on balancing hay to corn sites as well as on representing a range of field conditions (for example, PAW1 was noted to have experienced high erosion rates with a relatively large proportion of phosphorus output in a particulate form, whereas SHE1 was noted to have had a history of very low nutrient inputs). Some consideration was also given to selecting at least one site deemed representative of 'typical' corn and 'typical' hay field conditions (where 'typical' indicates that fields were managed to maximize crop production with relatively common operations and characteristics). Because the tile drained sites were predominantly in silage corn production, we gave preference to hay sites for the surface monitoring locations to achieve higher overall crop diversity. The result of this selection process was that edge-of-field sites SHE1, SHO1, FER1, CHA1, and PAW1 were chosen for model application and subsequent tasks (

Table 2). These five sites include three hay fields, a permanent corn field, and a corn into barley field with periods of record ranging from 2.5 years to 5 years.

In addition to Stone datasets, one site located in northern New York and maintained by the Miner Institute was included in the APEX calibration and validation efforts. This site is continuous corn with 3.5 years of concurrent surface and tile monitoring. Data for this site includes continuous flow monitoring and flow-based sampling of nutrients. Soil test P was measured each year of monitoring and the site had minimal gaps in data.

Table 1. Metadata on Stone monitored tile drained sites in the Vermont portion of the Lake Champlain Basin.

Site ID number	Selected?	Current crop or rotation (2017; 2018)	Monitoring data availability (MM/YY)	Resolution of flow data	Frequency of nutrient data	Prior conditions known?	Surface inlets or diversions present?
JBT01	Yes	soy; corn; NA	04/17 – 05/18	15 minutes	Weekly composite (grab during winter)	Soil test P; approximate past field condition known	No
JBT04	Yes	corn; NA; NA	04/17 – 12/17	15 minutes	Weekly composite (grab during winter)	Soil test P; approximate past field condition known	No
JBT05	Yes	corn; corn	04/17 – 11/18	15 minutes	Weekly composite (grab during winter)	Soil test P; approximate past field condition known	No
JBT07	Yes	corn; corn	04/17 – 11/18	15 minutes	Weekly composite (grab during winter)	Soil test P; approximate past field condition known	No
JBT11	Yes	alfalfa; alfalfa	04/17 – 11/18	15 minutes	Weekly composite (grab during winter)	Soil test P; approximate past field condition known	No
JBT18	Yes	hay; corn	04/17 – 11/18	15 minutes	Weekly composite (grab during winter)	No soil test P; approximate past field conditions known	No
JBT13	No	corn; corn	04/17 – 11/18	15 minutes	Weekly composite (grab during winter)	Soil test P; cover crop known; some direct manure into tiles observed	No
JBT02	No	soy; NA	04/17 – 05/18	15 minutes	Weekly composite (grab during winter)	Soil test P; approximate past field condition known	No
JBT06	No	corn; corn	04/17 – 05/18	1 minute (ultrasonic)	Weekly composite (grab during winter)	Soil test P; approximate past field condition known	Yes
JBT14	No	corn; corn	04/17 – 05/18	15 minutes	Weekly composite (grab during winter)	Soil test P; cover crop known	Yes
JBT16	No	corn; corn	04/17 – 11/18	15 minutes	Weekly composite (grab during winter)	Soil test P; approximate past field condition known	Yes
JBT19[1]	No	hay; corn; corn	04/17 – 01/18	15 minutes	Weekly composite (grab during winter)	No soil test P; approximate past field conditions known	Yes

Table 2. Metadata on Stone monitored edge-of-field sites in the Vermont portion of the Lake Champlain Basin.

Site ID	Selected?	Current crop or rotation (2013- end of study)	Monitoring data availability (MM/YY)	Resolution of flow data	Frequency of nutrient data	Notes
SHE1	Yes	Continuous hay	10/12 – 05/18	1 – 15 minutes, depending on stage	Event-based	small site; low nutrient inputs; reliable data
SHO1	Yes	Continuous hay	10/12 – 07/15	1 – 15 minutes, depending on stage	Event-based	small site; heavy soils; infrequent runoff events
FER1	Yes	Rotated hay (organic)	11/12- 12/15	1 – 15 minutes, depending on stage	Event-based	large site; heavy soils; frequent runoff events; representative of 'typical' hay field
CHA1	Yes	Corn (2015-17); fallow (2018); barley (2019)	09/15 – 12/18	1 – 15 minutes, depending on stage	Event-based	representative of 'typical' corn field
PAW1	Yes	Continuous corn	10/12 – 12/15	1 – 15 minutes, depending on stage	Event-based	erosion prone (saw major erosion); significant particulate P and high TSS
WAS1	No	Continuous corn	10/13 - spring 2016	1 – 15 minutes, depending on stage	Event-based	large site; fine textured soils
WAS2	No	Continuous corn	10/13 - spring 2016	1 – 15 minutes, depending on stage	Event-based	outlet of ineffective sediment basin; below WAS1
SHE2	No	Continuous hay	10/12 – 05/18	1 – 15 minutes, depending on stage	Event-based	small site; wet
SHO2	No	Continuous hay	10/12 – 07/15	1 – 15 minutes, depending on stage	Event-based	extremely small site, very infrequent runoff events
WIL1	No	Continuous corn	10/12 – 10/18	1 – 15 minutes, depending on stage	Event-based	Small site; had to berm (very flat); infrequent runoff events
WIL2	No	Continuous corn	10/12 – 10/18	1 – 15 minutes, depending on stage	Event-based	small site; lighter texture soils
FRA1	No	Strip cropped - corn/hay	10/12 – 12/15	1 – 15 minutes, depending on stage	Event-based	dendritic tile drain (not monitored); crops planted in strips and alternated every few years
FRA2	No	Strip cropped - corn/hay	10/12 – 12/15	1 – 15 minutes, depending on stage	Event-based	dendritic tile drain (not monitored); crops planted in strips and alternated every few years
FER2	No	Rotated hay (organic)	11/12- 12/15	1 – 15 minutes, depending on stage	Event-based	small site; infrequent runoff events
CHA2	No	Corn (2015-17); fallow (2018); barley (2019)	09/15 – 12/18	1 – 15 minutes, depending on stage	Event-based	representative of 'typical' corn field; somewhat more sloped than CHA1; runoff prone
PAW2	No	continuous corn	10/12 – 12/15	1 – 15 minutes, depending on stage	Event-based	very small site; data gaps

3.1.2. Compilation and Evaluation of Data

Field level information as well as monitoring data was collected for the tile drained and edge-of-field monitoring sites managed by Stone as part of previous and existing monitoring projects (Braun et al., 2015; Braun and Meals, 2019; Braun et al., 2019). This included information on soils and field conditions, agronomic operations and management, meteorological data, and monitoring (flow and P) data. Information used to set up and initially parameterize the APEX models for selected sites were obtained from documented field efforts and/or discussion with Dave Braun (Stone Environmental monitoring program lead).

Monitoring data obtained through the Stone monitoring program are described in detail in associated reports for tile sites (Braun et al., 2019) and edge-of-field sites (Braun et al., 2016; Braun and Meals, 2019). These reports describe sampling as well as data aggregation and processing methods. For this work, monitoring data for tile drained sites was obtained as monthly summaries, where monthly flow volume (L) and total P load (kg) were used for comparison to APEX outputs. Edge-of-field data was obtained as event summaries, where flow volume (L) and total P load (g) were used for comparison to APEX outputs. Further details on extraction of APEX output to appropriately match monitoring data is provided in Section 3.2.2.

Site-specific meteorological data was available for the edge-of-field sites, including temperature and precipitation at 15-minute resolution (Braun et al., 2016; Braun and Meals, 2019). This data was compiled into a single time series for each site and aggregated to a daily resolution. Model inputs included daily total precipitation, daily maximum temperature, and daily minimum temperature. Observed temperature and precipitation data was also reviewed for data gaps and where found were filled with data from the nearest complete dataset from NOAA station data. Table 3 shows identified gaps in data and what data was used to fill those gaps.

All tile drained sites monitored by Stone were located in the Jewett Brook watershed (VT). For these sites, precipitation data was obtained from a weather monitoring station in St. Albans, maintained By Stone Environmental and Fitzgerald Environmental Associates as part of a project with VT DEC to monitor precipitation and streamflow (http://vt-ms4-flow.stone-env.com/FlowDev/index.html#). This data was available at 5-minute resolution and again aggregated to daily totals as an input for APEX models. Because temperature was not monitored at this location, the nearest complete dataset from NOAA station data was used (for Jewett Brook sites, this was the Burlington International Airport station, USW00014742).

Information and data related to the Miner site in New York was provided by Laura Klaiber (personal communication, 2019), including site conditions (location, size, soils, slope), agronomic operations information (tillage, manure/fertilizer application dates and amounts), as well as event sampling information. Temperature and precipitation were recorded onsite and provided to Stone as daily total precipitation, as well as average, maximum, and minimum daily temperature. Daily flow monitoring (L/day) and event-based total P loads (g) were provided for both tile drainage and surface runoff.

Table 3. Meteorological data gaps.

Site	Date(s) where onsite temperature and/or precipitation were missing	Substituted Precipitation Source, Station ID (Location)[1]	Substituted Temperature Source, Station ID (Location)[1]
SHO1	11/21/2013	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	11/22/2013	US1VTAD0005 (Orwell)	USC00438597 (Vergennes)
	11/23/2013-11/24/2013	USC00438597 (Vergennes)	USC00438597 (Vergennes)
	3/25/15-3/27/2015	Onsite	USC00438597 (Vergennes)
	3/28/2015	Onsite	USW00014742 (S. Burlington Airport)
	3/29/2015-4/3/2015	Onsite	USC00438597 (Vergennes)
	4/4/2015-4/6/2015	Onsite	USW00014742 (S. Burlington Airport)
	4/6/2015-5/1/2015	Onsite	USC00438597 (Vergennes)
	4/29/2016-5/2/2016	US1VTAD0005 (Orwell)	USC00438597 (Vergennes)
CHA1	10/13/15-12/31/15	Onsite	USW00014742 (S. Burlington Airport)
	6/8/2016; 6/11/2016-7/1/2016; 7/6/2016-7/8/2016	US1VTCH0003 (Charlotte)	USW00014742 (S. Burlington Airport)
	6/9/2016-6/10/2019; 7/2/2016-7/11/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	12/16/2016-2/1/2017	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	11/23-12/15/2016	Onsite	USW00014742 (S. Burlington Airport)
	12/16-12/21/2016; 1/3/2017; 1/8-1/9/2017; 1/15-1/21/2017;1/29-1/31/2017	US1VTCH0003 (Charlotte)	USW00014742 (S. Burlington Airport)
	12/22/2016-1/2/2017; 1/4-1/7/2017;1/10-1/14/2017;1/22-1/28/2017;2/1/2017	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	2/5/2018; 2/11-2/12/2018; 3/4-3/6/2018; 3/18-3/29/2018;4/16/2018;4/22-4/30/2018	US1VTCH0003 (Charlotte)	USW00014742 (S. Burlington Airport)
	2/6-2/10/2018; 2/13-3/3/2018; 3/7-3/17/2018; 3/20-4/15/2018;4/17-4/21/2018	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	10/13/2015-6/7/2016	Onsite	USW00014742 (S. Burlington Airport)
FER1	N/A		
SHE1	6/8-7/7/2014	US1VTCH0003 (Charlotte)	USW00014742 (S. Burlington Airport)
	3/21-4/1/2018; 4/16/2018; 4/22-4/24/2018	US1VTCH0003 (Charlotte)	USW00014742 (S. Burlington Airport)
	4/1-4/15/2018; 4/17-4/21/2018	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
PAW1	3/20, 3/30, 3/31, 4/5, 4/8, 4/9, 4/10, 4/13, 4/14, 4/15, 4/16, 4/23, 4/26, 4/27 2014	US1VTAD0005 (Orwell)	USW00014742 (S. Burlington Airport)
	3/4-4/28/2014 (except for dates above)	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	4/20-4/22/13	US1VTAD0005 (Orwell)	USC00438597 (Vergennes)
	4/19/2013; 4/23/2013	USC00438597 (Vergennes)	USC00438597 (Vergennes)

Site	Date(s) where onsite temperature and/or precipitation were missing	Substituted Precipitation Source, Station ID (Location)[1]	Substituted Temperature Source, Station ID (Location)[1]
St Albans (tile drained sites)	2016-2018	Onsite	USW00014742 (S. Burlington Airport)
	1/21/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	2/11/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	5/1/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	5/13/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	5/14/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	5/15/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	5/16/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	6/1/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	6/18/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	6/22/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	7/13/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	9/8/2016	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	1/31/2017	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	2/1/2017	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	2/2/2017	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	2/3/2017	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	2/4/2017	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	2/5/2017	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	2/6/2017	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	2/7/2017	USW00014742 (S. Burlington Airport)	USW00014742 (S. Burlington Airport)
	5/20-5/25/2017	USW00014742 (S. Burlington Airport)	onsite

[1]For both precipitation and temperature, if listed as 'onsite', onsite data was available, otherwise the station ID and name of substituted data is provided.

3.2. Model Calibration and Validation with Monitoring Data

3.2.1. APEX Model Parameterization from Field Data

Each of the 12 field sites were setup for APEX using the best available information concerning the site conditions and agronomic operations. Overall, the level of detail in the site monitoring data for the edge-of-field monitoring sites (CHA1, FER1, PAW1, SHE1, SHO1, and M1) was higher than that for the tile drained monitoring sites. The greatest uncertainty in the tile drained monitoring sites concerned the nutrient inputs from manure and commercial fertilizers. Manure nutrient analyses were unavailable for the tile drained monitoring sites, and application rates were often estimated. Application rates and specific types of commercial fertilizer were also estimated in many cases. Furthermore, the specifics of tillage practices were not always known. For the edge-of-field sites and the Miner site in New York state, manure nutrient analyses were often available, and records on application rates was often more complete. The APEX agronomic operation schedules for each site were then developed for all sites using the best available information for each field site.

Farm-PREP was used to generate the initial APEX model setup for each site, with the exception of the Miner Site in New York, which was setup manually due to New York datasets being unavailable in Farm-PREP. Each field was delineated in Farm-PREP's web interface and site-specific soil test P was entered where known (this was available for 5 of the 6 Stone monitored tile drained sites and all 5 edge-of-field sites, as well as the Miner site, see Table 4). Operation schedules including crop rotations, tillage, and manure/fertilizer applications were set up manually based on site-specific information (Section 3.2.1.2). An assessment was created and run for each field, thereby creating a downloadable file deck comprising all necessary APEX model files. These 12 APEX models were then extracted from Farm-PREP so that the models could be run through batch execution processes on desktop computers. Subsequent sections describe manual and site-specific modifications to APEX models for each site.

3.2.1.1. Soils

Soil parameters were largely obtained via Farm-PREP's interface, which queries the NRCS SSURGO database for representative values associated with the dominant soil polygon within each delineated field. As the Miner site is located in New York, the selection of SSURGO parameters was done outside of Farm-PREP but using the same methodology. For 11 of 12 sites, site-specific soil test P values were available and used to set the initial soluble P concentration in all soil layers based on the equation presented in Stone Environmental, Inc. (2015). This required a conversion from the Modified Morgan's soil P concentration to a Mehlich 3 soil P concentration equivalent using the following equation (Winchell et al., 2011):

$$Mehlich3 = 6.718 \times Modified\ Morgan - 11.83 \times pH - 32.757 \times \frac{Modified\ Morgan}{Aluminum} + 90.73$$

The initial soluble mineral P value in APEX (SSF parameter) was then set to 50% of the Mehlich 3 concentration as recommended by Vadas and White (2010) for initializing soluble, active, and stable soil P pools. Another soil parameter dependent upon the initial soluble P concentration is the phosphorus sorption ration (PSP parameter). The PSP value has also shown to be a function of clay content and organic carbon and the equation proposed by Vadas and White (2010) was used to calculate PSP for each soil layer according to the equation below:

$$PSP = -0.053 \times \log(Clay) + 0.001 \times Soluble\ P - 0.029 \times Organic\ C + 0.42$$

While Vadas and White (2010) calculated PSP values as low as 0.06, we elected to constrain PSP values used in APEX to be no lower than 0.10, as the default value for this parameter is typically 0.40. Values of key soil parameters used in the APEX models are shown in Table 4.

Additional parameters for tile drained sites included depth to drainage system and approximate spacing of the tile lines and were based on known information about sites (either from information gathered in Stone monitoring efforts or provided by the Miner Institute). In the APEX model, the time required for the tile system to drain the soil to field capacity is a required input. Based on recommended APEX default values, our experience in parameterizing APEX, and observed trends in the monitoring data, we estimated this value to be 2 days for tile spacing of $<=$ 30 ft, 3 days for tile spacing between 30 ft and 60 ft, and 4 days for tile spacing of greater than 60 ft. These values are also provided in Table 4.

Table 4. Soil and tile drainage parameters (by soil layer where applicable) used in initial parameterization of APEX models.

Site	Depth to Bottom of Soil Layer (m)	Percent Sand (%)	Percent Silt (%)	Organic Carbon Concentration (%)	Saturated Hydraulic Conductivity (mm/h)	Wet Bulk Density (g/cm3)	Soil pH	[1]Modified Morgan Soil Test P (ppm)	Initial Soluble P Concentration (g/Mg)	Phosphorus Sorption Ratio	Tile Drainage Spacing (ft)	Depth to Tile (ft)
JBT01	0.15, 0.91, 1.52	31.2, 7.4, 11.4	26.8, 17.6, 13.6	3.48, 0.29, 0.29	3.30, 0.76, 0.76	1.18, 1.50, 1.45	6.5, 6.5, 8.2	7.2	24.90, 16.50, 15.91	0.15, 0.20, 0.20	25	4
JBT04	0.15, 0.91, 1.52	31.2, 7.4, 11.4	26.8, 17.6, 13.6	3.48, 0.29, 0.29	3.30, 0.76, 0.76	1.18, 1.50, 1.45	6.5, 6.5, 8.2	4.5	20.67, 14.80, 14.39	0.14, 0.20, 0.20	25	4
JBT05	0.15, 0.91, 1.52	31.2, 7.4, 11.4	26.8, 17.6, 13.6	3.48, 0.29, 0.29	3.30, 0.76, 0.76	1.18, 1.50, 1.45	6.5, 6.5, 8.2	2	12.98, 10.15, 9.95	0.13, 0.19, 0.19	35	3.5
JBT07	0.15, 0.81, 1.52	31.2, 7.4, 11.4	26.8, 17.6, 13.6	5.80, 0.73, 0.15	2.54, 0.76, 0.76	1.30, 1.38, 1.38	6.5, 6.7, 7.0	12	43.29, 26.48, 25.11	0.10, 0.20, 0.21	40	3.5
JBT11	0.20, 0.64, 1.12	44.3, 30.9, 45.7	40.7, 56.6, 41.8	3.19, 0.29, 0.15	33.02, 8.38, 3.30	1.25, 1.35, 1.78	6.5, 6.5, 7.5	4	19.04, 12.98, 12.98	0.20, 0.29, 0.29	40	3.5
JBT18	0.15, 0.91, 1.52	31.2, 7.4, 11.4	26.8, 17.6, 13.6	3.48, 0.29, 0.29	3.30, 0.76, 0.76	1.18, 1.50, 1.45	6.5, 6.5, 8.2	5 (Farm-PREP default value)	22.07, 14.99, 14.50	0.14, 0.20, 0.20	80	3
CHA1	0.15, 0.36, 0.63, 1.65	15.9, 7.4, 7.4, 7.4	25.6, 17.6, 17.6, 17.6	2.32, 0.73, 0.73, 0.15	8.38, 2.54, 2.54, 0.76	1.30, 1.38, 1.38, 1.38	5.9, 5.9, 7.0, 8.2	4.2	11.83, 7.71, 6.42, 6.42	0.15, 0.15, 0.18, 0.19	N/A	N/A
FER1	0.20, 0.71, 1.65	5.3, 7.4, 7.4	44.7, 17.6, 17.6	5.51, 0.73, 0.15	2.54, 0.76, 0.76	1.30, 1.38, 1.38	6.5, 6.7, 7.0	2.3	14.93, 11.51, 11.51	0.1, 0.18, 0.20	N/A	N/A
PAW1	0.20, 0.69, 1.52	46.0, 68.5, 32.9	44.0, 21.5, 57.1	2.32, 0.61, 0.15	33.02, 33.02, 0.76	1.15, 1.45, 1.85	6.5, 6.5, 7.3	8.3	19.36, 9.00, 9.00	0.25, 0.29, 0.30	N/A	N/A
SHE1	0.20, 0.71, 1.65	5.3, 7.4, 7.4	44.7, 17.6, 17.6	5.51, 0.73, 0.15	2.54, 0.76, 0.76	1.30, 1.38, 1.38	6.5, 6.7, 7.0	8.4	18.94, 10.56, 10.56	0.07, 0.18, 0.20	N/A	N/A
SHO1	0.15, 0.41, 0.74, 1.65	15.9, 7.4, 7.4, 7.4	25.60, 17.60, 17.60, 17.60	2.32, 0.73, 0.73, 0.15	8.38, 2.54, 2.54, 0.76	1.30, 1.38 ,1.38 1.38	5.9, 5.9, 7.0, 8.2	1.4	13.60, 11.86, 11.44, 11.44	0.15, 0.18, 0.18, 0.2	N/A	N/A

Site	Depth to Bottom of Soil Layer (m)	Percent Sand (%)	Percent Silt (%)	Organic Carbon Concentration (%)	Saturated Hydraulic Conductivity (mm/h)	Wet Bulk Density (g/cm3)	Soil pH	[1]Modified Morgan Soil Test P (ppm)	Initial Soluble P Concentration (g/Mg)	Phosphorus Sorption Ratio	Tile Drainage Spacing (ft)	Depth to Tile (ft)
M1	0.25, 0.38, 0.48, 0.89, 2.00	44.0, 44.0, 59.0, 44.0, 44.0	44.0, 44.0, 32.0, 44.0, 44.0	2.33, 0.58, 0.29, 0.12, 0.12	50.40, 50.40, 72.00, 50.40, 3.28	1.27, 1.47, 1.51, 1.54, 1.95	7.0, 7.0, 7.0, 7.0, 7.0	2.5	9.16, 6.56, 6.56, 6.56, 6.56, 6.56	0.23, 0.28, 0.30, 0.29, 0.29	35	4

[1] While soil test P was not an APEX input, values shown here were specific to each site and used to determine initial soluble P concentrations.

3.2.1.2. Agronomic Operations

Agronomic information used as the starting point for APEX operations schedules are described in associated reports for tile sites (Braun et al., 2019) and edge-of-field sites (Braun et al., 2016; Braun and Meals, 2019). This management information was converted into APEX inputs that included date of operation, crop type, operation type, equipment, fertilizer or manure type, and application rate (for manure/fertilizer). Where specific information was not available (e.g. type of equipment used), it was assigned based on consultation with Dave Braun and/or by assuming practices typical in Vermont that are used in Farm-PREP simulations. Table 5 - Table 16 shows operations schedules used in APEX models for each site.

Table 5. Management operations for APEX model of JBT01.

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight, lbs/acre)
5/6/2017	Tillage	Tandem disk	Soybeans		
5/15/2017	Planting	Planter, regular	Soybeans		
5/16/2017	Fertilizer application		Soybeans	10-20-10	150
10/3/2017	Harvest	Combine	Soybeans		
10/24/2017	Tillage	Moldboard	Soybeans		
11/15/2017	Manure application		Soybeans	VTP2O5-LowDM	1743
5/9/2018	Tillage	Tandem disk	Corn (silage)		
5/15/2018	Planting	Planter, regular	Corn (silage)		
5/16/2018	Fertilizer application		Corn (silage)	10-20-10	150
6/30/2018	Fertilizer application		Corn (silage)	46-00-00	217
10/10/2018	Harvest	Silage harvester	Corn (silage)		

[1]Manure characteristics are described in Section 3.2.1.3.

Table 6. Management operations for APEX model of JBT04.

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight, lbs/acre)
5/6/2017	Tillage	Tandem disk	Corn (silage)		
5/15/2017	Planting	Planter, regular	Corn (silage)		
5/16/2017	Fertilizer application		Corn (silage)	10-20-10	150
6/30/2016	Fertilizer application		Corn (silage)	46-00-00	217
11/20/2017	Harvest	Silage harvester	Corn (silage)		
11/22/2017	Tillage	Chisel	Corn (silage)		

Table 7. Management operations for APEX model of JBT05.

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight, lbs/acre)
5/15/2017	Planting	Planter, regular	Corn (silage)		
5/15/2017	Fertilizer application		Corn (silage)	10-20-10	150
6/23/2017	Fertilizer application		Corn (silage)	46-00-00	217
10/10/2017	Harvest	Silage harvester	Corn (silage)		
10/12/2017	Manure application			VTP2O5-LowDM	871
10/24/2017	Manure application	Injection		VTP2O5-LowDM	871
10/25/2017	Planting	Broadcast seeder	Rye		
5/22/2018	Tillage	Tandem disk	Corn (silage)		

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight, lbs/acre)
5/23/2018	Planting	Planter, regular	Corn (silage)		
6/23/2018	Fertilizer application		Corn (silage)	46-00-00	217
10/10/2018	Harvest	Silage harvester	Corn (silage)		

[1]Manure characteristics are described in Section 3.2.1.3.

Table 8. Management operations for APEX model for JBT07.

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight, lbs/acre)
5/6/2017	Tillage	Tandem disk	Corn (silage)		
5/15/2017	Planting	Planter, regular	Corn (silage)		
5/15/2017	Fertilizer application		Corn (silage)	10-20-10	83
5/15/2017	Fertilizer application		Corn (silage)	0-0-100	83
7/15/2017	Manure application	Injection	Corn (silage)	VTP2O5-LowDM	1494
10/17/2017	Harvest	Silage harvester	Corn (silage)		
11/20/2017	Tillage	Chisel	Corn (silage)		
5/16/2018	Manure application		Corn (silage)	VTP2O5-LowDM	1494
5/20/2018	Tillage	Moldboard	Corn (silage)		
5/23/2018	Planting	Planter, regular	Corn (silage)		
6/20/2018	Fertilizer application		Corn (silage)	46-00-00	200
9/20/2018	Harvest	Silage harvester	Corn (silage)		

[1]Manure characteristics are described in Section 3.2.1.3.

Table 9. Management operations for APEX model of JBT11.

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight, lbs/acre)
7/5/2017	Cutting	Baler	Alfalfa		
7/10/2017	Fertilizer application		Alfalfa	21-00-50	250
8/30/2017	Cutting	Baler	Alfalfa		
8/31/2017	Fertilizer application		Alfalfa	21-00-50	250
10/24/2017	Cutting	Baler	Alfalfa		
6/20/2018	Cutting	Baler	Alfalfa		
7/6/2018	Fertilizer application		Alfalfa	46-00-00	200
7/29/2018	Cutting	Baler	Alfalfa		
8/29/2018	Cutting	Baler	Alfalfa		
10/12/2018	Cutting	Baler	Alfalfa		

Table 10. Management operations for APEX model of JBT18.

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight, lbs/acre)
8/30/2017	Cutting	Baler	Red clover		
10/24/2017	Cutting	Baler	Red clover		
5/20/2018	Manure application		Corn (silage)	Chicken manure	195
5/24/2018	Tillage	Tandem disk	Corn (silage)		
5/25/2018	Planting	Planter, regular	Corn (silage)		
7/2/2018	Cultivate	Cultivator	Corn (silage)		

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight, lbs/acre)
7/13/2018	Fertilizer application		Corn (silage)	46-00-00	100
12/30/2018	Harvest	Silage harvester	Corn (silage)		

Table 11. Management operations for APEX model of CHA1.

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight, lbs/acre)
5/10/2015	Manure application		Corn (silage)	CHA1a	996
5/15/2015	Fertilizer application		Corn (silage)	18-20-60	150
5/20/2015	Tillage	Tandem disk	Corn (silage)		
5/22/2015	Planting	Planter, regular	Corn (silage)		
7/10/2015	Fertilizer application		Corn (silage)	46-00-00	150
9/16/2015	Harvest	Silage harvester	Corn (silage)		
9/18/2015	Planting	Planter, regular	Rye		
10/28/2015	Manure application		Rye	CHA1a	996
5/15/2016	Manure application		Corn (silage)	CHA1a	1992
5/18/2016	Planting	Planter, no-till	Corn (silage)		
5/26/2016	Fertilizer application	(trailer)	Corn (silage)	46-00-00	50
8/31/2016	Planting	Aerial seeding	Rye		
9/26/2016	Harvest	Silage harvester	Corn (silage)		
10/2/2016	Manure application		Rye	CHA1a	1992
5/15/2017	Manure application		Rye	CHA1a	1992
5/18/2017	Planting	Planter, regular	Corn (silage)		
11/9/2017	Harvest	Silage harvester	Corn (silage)		

Table 12. Management operations for APEX model of FER1.

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight, lbs/acre)
4/12/2012	Tillage	Tandem disk	Red Clover		
4/16/2012	Planting	Planter, regular	Red Clover		
7/4/2012	Cutting	Baler	Red Clover		
9/1/2012	Cutting	Baler	Red Clover		
4/28/2013	Interseeding	Broadcast seeder	Red Clover		
6/18/2013	Cutting	Baler	Red Clover		
7/24/2013	Cutting	Baler	Red Clover		
8/24/2013	Cutting	Baler	Red Clover		
9/19/2013	Cutting	Baler	Red Clover		
10/11/2013	Fertilizer application		Red Clover	0-1-3	4000
12/5/2013	Manure application		Red Clover	VTP2O5-LowDM	996
6/6/2014	Cutting	Baler	Red Clover		
7/9/2014	Cutting	Baler	Red Clover		
8/18/2014	Cutting	Baler	Red Clover		
10/12/2014	Cutting	Baler	Red Clover		
10/20/2014	Fertilizer application		Red Clover	0-1-3	4000
6/17/2015	Cutting	Baler	Red Clover		
8/16/2015	Cutting	Baler	Red Clover		
9/15/2015	Manure application		Red Clover	VTP2O5-LowDM	1494

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight, lbs/acre)
10/23/2015	Cutting	Baler	Red Clover		
10/27/2015	Manure application		Red Clover	VTP2O5-LowDM	1046

[1]*Manure characteristics are described in Section 3.2.1.3.*

Table 13. Management operations for APEX model of PAW1.

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight lbs/acre)
5/12/2012	Manure application		Corn (silage)	VTP2O5-LowDM	2324
5/12/2012	Tillage	Chisel	Corn (silage)		
5/29/2012	Planting	Planter, regular	Corn (silage)		
5/29/2012	Fertilizer application		Corn (silage)	30-10-20	200
9/27/2012	Harvest	Silage harvester	Corn (silage)		
5/2/2013	Manure application		Corn (silage)	VTP2O5-LowDM	2615
5/3/2013	Tillage	Chisel	Corn (silage)		
5/8/2013	Planting	Planter, regular	Corn (silage)		
5/8/2013	Fertilizer application		Corn (silage)	27-9-18	225
10/1/2013	Harvest	Silage harvester	Corn (silage)		
10/15/2013	Planting	Broadcast Seeder	Winter Wheat		
5/13/2014	Tillage	Tandem disk	Corn (silage)		
5/13/2014	Manure application		Corn (silage)	VTP2O5-LowDM	2615
5/13/2014	Tillage	Tandem disk	Corn (silage)		
5/16/2014	Planting	Planter, regular	Corn (silage)		
5/16/2014	Fertilizer application		Corn (silage)	27-9-18	221
9/20/2014	Harvest	Silage harvester	Corn (silage)		
9/23/2014	Planting	Broadcast Seeder	Rye		
5/10/2015	Manure application		Corn (silage)	VTP2O5-LowDM	2615
5/10/2015	Tillage	Chisel	Corn (silage)		
5/15/2015	Tillage	Tandem disk	Corn (silage)		
5/17/2015	Planting	Planter, regular	Corn (silage)		
5/17/2015	Fertilizer application		Corn (silage)	27-9-18	210
9/17/2015	Harvest	Silage harvester	Corn (silage)		
9/29/2015	Planting	Broadcast Seeder	Rye		

[1]*Manure characteristics are described in Section 3.2.1.3.*

Table 14. Management operations for APEX model of SHE1.

Date	Type of operation	Equipment	Crop	Fertilizer/ Manure type[1]	Application rate (dry weight, lbs/acre)
6/9/2012	Cutting	Baler	Smooth Brome Grass		
7/24/2012	Cutting	Baler	Smooth Brome Grass		
9/3/2012	Manure application		Smooth Brome Grass	SHE1-a	923
7/13/2013	Cutting	Baler	Smooth Brome Grass		
8/2/2013	Manure application		Smooth Brome Grass	SHE1-a	1212
9/3/2013	Cutting	Baler	Smooth Brome Grass		
6/8/2014	Cutting	Baler	Smooth Brome Grass		
6/10/2014	Aeration	Vertical tillage/Aerator	Smooth Brome Grass		
6/10/2014	Manure application		Smooth Brome Grass	SHE1-b	3700
7/17/2014	Cutting	Baler	Smooth Brome Grass		
8/27/2014	Cutting	Baler	Smooth Brome Grass		

Date	Type of operation	Equipment	Crop	Fertilizer/ Manure type[1]	Application rate (dry weight, lbs/acre)
10/21/2014	Manure application		Smooth Brome Grass	SHE1-c	717
6/3/2015	Cutting	Baler	Smooth Brome Grass		
7/16/2015	Cutting	Baler	Smooth Brome Grass		
7/27/2015	Aeration	Vertical tillage/Aerator	Smooth Brome Grass		
7/29/2015	Manure application		Smooth Brome Grass	SHE1-d	651
8/30/2015	Cutting	Baler	Smooth Brome Grass		
10/19/2015	Aeration	Vertical tillage/Aerator	Smooth Brome Grass		
10/19/2015	Manure application		Smooth Brome Grass	SHE1-e	3249

[1]Manure characteristics are described in Section 3.2.1.3.

Table 15. Management operations for APEX model of SHO1.

Date	Type of operation	Equipment	Crop	Fertilizer/ Manure type[1]	Application rate (dry weight, lbs/acre)
5/18/2012	Cutting	Baler	Smooth Brome Grass		
5/25/2012	Fertilizer application		Smooth Brome Grass	46-00-00	150
7/2/2012	Manure application		Smooth Brome Grass	VTP2O5-HighDM	2905
7/4/2012	Cutting	Baler	Smooth Brome Grass		
8/21/2012	Cutting	Baler	Smooth Brome Grass		
11/20/2012	Cutting	Baler	Smooth Brome Grass		
4/15/2013	Fertilizer application		Smooth Brome Grass	46-00-00	150
5/18/2013	Cutting	Baler	Smooth Brome Grass		
7/12/2013	Cutting	Baler	Smooth Brome Grass		
7/20/2013	Manure application		Smooth Brome Grass	VTP2O5-HighDM	2615
8/16/2013	Cutting	Baler	Smooth Brome Grass		
9/29/2013	Cutting	Baler	Smooth Brome Grass		
10/14/2013	Manure application		Smooth Brome Grass	VTP2O5-HighDM	2498
5/29/2014	Cutting	Baler	Smooth Brome Grass		
6/4/2014	Fertilizer application		Smooth Brome Grass	46-00-00	150
6/5/2014	Manure application		Smooth Brome Grass	VTP2O5-HighDM	2905
7/5/2014	Cutting	Baler	Smooth Brome Grass		
7/8/2014	Manure application		Smooth Brome Grass	VTP2O5-HighDM	2905
8/11/2014	Cutting	Baler	Smooth Brome Grass		
8/12/2014	Fertilizer application		Smooth Brome Grass	46-00-00	150
9/26/2014	Cutting	Baler	Smooth Brome Grass		
10/29/2014	Aeration	Vertical tillage/Aerator	Smooth Brome Grass		
10/30/2014	Manure application		Smooth Brome Grass	VTP2O5-HighDM	2905
4/17/2015	Fertilizer application		Smooth Brome Grass	46-00-00	150
6/2/2015	Cutting	Baler	Smooth Brome Grass		
7/16/2015	Cutting	Baler	Smooth Brome Grass		
7/17/2015	Aeration	Vertical tillage/Aerator	Smooth Brome Grass		

Date	Type of operation	Equipment	Crop	Fertilizer/ Manure type[1]	Application rate (dry weight, lbs/acre)
7/18/2015	Manure application		Smooth Brome Grass	VTP2O5-HighDM	3254
8/18/2015	Cutting	Baler	Smooth Brome Grass		
11/1/2015	Aeration	Vertical tillage/Aerator	Smooth Brome Grass		
11/1/2015	Manure application		Smooth Brome Grass	VTP2O5-HighDM	3254

[1]*Manure characteristics are described in Section 3.2.1.3.*

Table 16. Management operations for APEX model of Miner site.

Date	Type of operation	Equipment	Crop	Fertilizer/Manure type[1]	Application rate (dry weight, lbs/acre)
5/28/2015	Planting	Planter, regular	Corn (silage)		
5/28/2015	Fertilizer application		Corn (silage)	23-12-18	150
7/3/2015	Fertilizer application		Corn (silage)	32-00-00	250
9/27/2015	Harvest	Silage harvester	Corn (silage)		
10/20/2015	Manure application		Corn (silage)	Miner2	1660
5/19/2016	Tillage	Moldboard	Corn (silage)		
5/23/2016	Planting	Planter, regular	Corn (silage)		
5/23/2016	Fertilizer application		Corn (silage)	23-12-18	150
7/3/2016	Fertilizer application		Corn (silage)	32-00-00	250
9/27/2016	Harvest	Silage harvester	Corn (silage)		
5/24/2017	Manure application		Corn (silage)	Miner1	19800
5/25/2017	Tillage	Moldboard	Corn (silage)		
5/28/2017	Planting	Planter, regular	Corn (silage)		
5/28/2017	Fertilizer application		Corn (silage)	23-12-18	100
7/7/2017	Fertilizer application		Corn (silage)	32-00-00	281
9/29/2017	Harvest	Silage harvester	Corn (silage)		
11/21/2017	Manure application		Corn (silage)	Miner2	2075
11/22/2017	Tillage	Moldboard plow	Corn (silage)		
5/10/2018	Tillage	Moldboard plow	Corn (silage)		
5/17/2018	Planting	Planter, regular	Corn (silage)		
5/17/2018	Fertilizer application		Corn (silage)	23-12-18	100
6/26/2018	Fertilizer application		Corn (silage)	32-00-00	141
9/20/2018	Harvest	Silage harvester	Corn (silage)		
12/21/2018	Manure application		Corn (silage)	Miner2	2075

[1]Manure characteristics are described in Section 3.2.1.3.

3.2.1.3. Manure Management

APEX requires information describing the fraction of nutrient contents (mineral and organic N, mineral and organic P, as well as mineral K, ammonia N, and organic C fractions) of each manure product applied to a field. Manure nutrient contents were specific to each tile drained or edge-of-field site and while specific information on nutrient contents of manure applied was available for some sites, for many sites only manure application amounts or rates were known. For some manures, certain physical characteristic/s (e.g. dry matter content) were also known.

For manure applications where little or no nutrient content information was available, two types of manure were parameterized to represent standard Vermont manures with a high dry matter content (representative of semi-solid manure) and a low dry matter content manure (representative of liquid dairy manure). If dry matter content was unknown, liquid dairy manure was classified as either having low dry matter (assume < 5% dry matter) or high dry matter (assume 5-10 % dry matter) and assigned 3% and 7%, respectively. Little information was known about specific manure characteristics or nutrient content at the tile drained sites, except in some cases there was indication manure being either semi-solid or liquid. If manure was in liquid form, VTP2O5-LowDM was used to parameterize manure applications, while if manure was a semi-solid product, VTP2O5-HighDM was used.

In order to calculate nutrient ratios for Vermont standard manure types, as well as for site-specific manure when this information was not available, the following assumptions were made:

- Density of all manures was assumed to be 8.3 lbs/gal (Stone, 2015).
- The carbon to nitrogen ratio (C:N) for all manures was assumed to be 20 (Augustin and Rahman, 2010).
- The mineral P fraction of total P in manure is 64.9%, This is based on ratio of orthophosphorus to total phosphorus in dairy manure (ASCE, 2003)
- The fraction of ammonia N comprising the total mineral N portion of manure was set at 0.99 based on default manure parameterizations in SWAT and APEX.

Nutrient fractions used to represent the two standard Vermont manured (low and high dry matter products), as well as for site-specific manure, in APEX models are shown in Table 17. Details on known manure characteristics can be found in Braun et al. (2015), Braun and Meals (2019), and Braun et al. (2019).

Table 17. Nutrient fractions in manure and fertilizers used in APEX models for calibration/validation.

Application Type	Fertilizer/Manure Name	Mineral N (fraction)	Mineral P (fraction)	Mineral K (fraction)	Organic N (fraction)	Organic P (fraction)	Ammonia N (fraction of mineral N that is in form of ammonia)	Organic C (fraction)
Manure	VTP2O5-LowDM	0.020	0.005	0.050	0.029	0.003	0.990	0.586
	VTP2O5-HighDM	0.013	0.004	0.031	0.025	0.002	0.990	0.506
	PAW1 (same as VTP2O5-HighDM)	0.013	0.004	0.031	0.025	0.002	0.990	0.506
	SHE1a	0.030	0.008	0.076	0.044	0.004	0.990	0.880
	SHE1b	0.007	0.003	0.017	0.014	0.001	0.990	0.275
	SHE1c	0.030	0.004	0.076	0.044	0.002	0.990	0.880
	SHE1d	0.025	0.005	0.063	0.037	0.003	0.990	0.733
	SHE1e	0.018	0.004	0.042	0.034	0.002	0.990	0.681
	CHA1a	0.013	0.013	0.120	0.019	0.007	0.990	0.372
	Miner1	0.003	0.001	0.006	0.005	0.001	0.990	0.110
	Miner2	0.013	0.001	0.044	0.025	0.001	0.990	0.508
	Chicken	0.059	0.004	0.074	0.015	0.010	0.990	0.148
Commercial fertilizer	30-10-20	0.300	0.044	0.166	0.000	0.000	0.000	0.000
	27-9-18	0.270	0.039	0.149	0.000	0.000	0.000	0.000
	6-9-19	0.060	0.039	0.158	0.000	0.000	0.000	0.000
	18-20-60	0.100	0.087	0.083	0.000	0.000	0.000	0.000
	23-12-18	0.230	0.052	0.149	0.000	0.000	0.000	0.000
	21-00-50	0.210	0.000	0.415	0.000	0.000	0.000	0.000
	32-00-00	0.320	0.000	0.000	0.000	0.000	0.000	0.000
	Urea (46-00-00)	0.460	0.000	0.000	0.000	0.000	0.000	0.000
	Wood Ash (0-1-3)	0.000	0.004	0.025	0.000	0.000	0.000	0.000
	VTStarter (10-20-10)	0.100	0.087	0.083	0.000	0.000	0.000	0.000

3.2.2. Extraction and Processing of Monitoring Data for Model Comparison

The flow and total P monitoring data for all 12 sites were compiled. In the case of the surface runoff sites, the dates associated with each runoff event were identified (including one day before and one day after the recorded 'event' start and end dates). APEX model outputs were extracted for these same event dates (for edge-of-field sites) and used to extract APEX model outputs for comparison to monitoring data. In the case of tile drained sites (including the Miner site), continuous monitoring data was available. APEX model simulation flow and total P results and monitoring data observations were aggregated to annual sums for comparison and model calibration. Time periods modeled in APEX for each site were based on availability of both meteorological and flow/P monitoring data at each site and are shown in Table 1 and Table 2 for tile and edge-of-field sites, respectively.

3.2.3. APEX Calibration and Validation

3.2.3.1. Overall Approach

The calibration and validation of APEX sought to identify a global parameterization of the model that minimized model prediction bias across all 12 sites and minimized the magnitude in model error in annual total P load predictions. Secondarily, minimization of model predicted average annual flow bias and magnitude of the errors in annual flow were considered. The calibration/validation process occurred over the following stages: 1.) Initial model setup and parameterization, 2.) Manual model evaluation and calibration, 3.) Automatic calibration of global parameterization, 4.) Monte Carlo analysis of soils parameter uncertainty with global parameterization, 5.) Automatic calibration of site-specific parameterization, and 6.) Monte Carlo analysis of soils parameter uncertainty with site-specific parameterization.

A "global parameterization" refers to establishment of a single set of APEX parameters applied to all sites, specifically for those parameters that are not identified from site-specific data. Thus, soils, slope, weather, and agronomic practice information may vary across all sites, however the approach to processing and interpreting that data into APEX parameters must remain constant. There are a significant number of APEX "global" parameters that cannot be determined from available site-specific datasets. Some examples of these parameters include those found in the APEX "Control" input file (APEXCONT) and the APEX "Parm" input file (PARM1501). The APEXCONT file includes parameters such as which evapotranspiration estimation method to use, the method for calculating the slope steepness factor, and the method for calculating off-field erosion. The PARM1501 file includes over 100 parameters that affect behavior of all hydrological and biochemical processes in the model, including adjustment to runoff curve number initial abstraction, effects of crop height on crop/residue factor for erosion calculations, and rates of microbial decay of organic matter. These parameters in APEXCONT and PARM1501 input files were the focus of the global parameter calibrations.

A site-specific parameterization allows the entire APEX model parameter set to vary from site to site and recognizes that inherent variability and uncertainty in environmental processes can result in variability in the model parameters describing these processes. A limited site-specific calibration was conducted in this study to better understand how uncertainty in several "global" parameters impacts the APEX model predictions and comparisons with monitoring data.

Monte Carlo analyses were conducted for all 12 sites, focusing on a subset of important soil parameters for which the raw data sources (NRCS SSURGO) provides a range of expected values. These Monte Carlo analyses were conducted with both the global parameterization and the site-specific parameterization.

3.2.3.2. Manual Model Evaluation and Calibration

The manual model evaluation and calibration was an important component to the overall global parameterization and calibration. Overall model performance was measured based on a weighted average of model goodness of fit statistics where each of the 12 sites received an equal weight of 1/12. In the case of the Miner New York site, where both tile and surface flows and P loads were measured, the weight for that site was split equally between tile and surface fluxes. The goodness of fit statistics considered at this phase were the annual percent bias (PBIAS), calculated as Sum(Model-Predicted – Observed) / Sum(Observed), for flow and total P (TP), and the mean absolute annual error (MeanAbsError), calculated as Average(Abs(Model-Predicted – Observed)), in flow and total P. We determined that because of the wide range in the magnitude of the flows and total P loads across all 12 sites that the percent bias statistic had the potential to over-weight high percent errors with low magnitudes. The consideration of the mean absolute avoids this potential shortcoming of the percent bias statistic.

Many of the APEX parameters found in the APEXCONT and PARM1501 files were considered in the manual evaluation and calibration phase. The starting point for the APEXCONT and PARM1501 parameter values was the parameter set used in Farm-PREP, which were derived from default values in the APEX 1501 model. Parameters were modified in a one-at-a-time fashion, followed by simulation of all 12 sites and evaluation of the outputs and goodness of fit statistics. In addition to the flows and total P outputs and goodness of fit statistics, APEX-simulated crop yields were reviewed and compared with published values for Vermont (Bosworth and Darby, 2015; Cornell University, 2017; Cornell University, 2018; USDA, 2019). This process served several purposes. First, it allowed for the identification of any significant model issues or errors to be resolved and helped to understand the overall behavior of the model. Second, it allowed for the sensitivity of many parameters to be assessed. Finally, parameter choices that clearly led to improved overall model performance were determined. This provided a more solid starting point for a global parameterization to be established prior to automatic calibration of a smaller subset of parameters.

3.2.3.3. Automatic Calibration of Global Parameters

The automatic calibration approach was to sample a complete discretized parameter space for a subset of sensitive global parameters identified through the manual calibration process. The approach for sampling the parameter space and executing the model simulations was a “brute force” approach where all parameter combinations, based on the discretization interval of each parameter across its range, are evaluated.

Multiple rounds of automatic calibration were conducted. Initial rounds further explored the sensitivity of subsets of parameters and helped to identify values for these parameters that consistently resulted in model performance that minimized percent bias and mean absolute error for flow and total P. These initial automatic calibration rounds resulted in a final calibration round that focused on a smaller set of parameters and narrower ranges of those parameters. Table 18 below list the APEX model parameters considered over all rounds of calibration, with those included in the final round of automatic global calibration indicated.

Table 18. APEX parameters considered in automatic calibration.

Input File	Parameter ID	Parameter Definition	Final Calibration Round
APEXCONT	LBP	Soluble Phosphorus Runoff Estimate Equation	
APEXCONT	ISLF	Slope Length/Steepness Factor	
APEXCONT	IPRK	Soil Water Percolation Method	
APEXCONT	DRV	Equation for Water Erosion	
PARM1501	PARM(8)	Soluble Phosphorus Runoff Coefficient	

Input File	Parameter ID	Parameter Definition	Final Calibration Round
PARM1501	PARM(20)	Runoff Curve Number Initial Abstraction	X
PARM1501	PARM(23)	Hargreaves PET Equation Coefficient	X
PARM1501	PARM(29)	Biological Mixing Efficiency	
PARM1501	PARM(46)	RUSLE C-factor Coefficient, Residue Function Factor	
PARM1501	PARM(47)	RUSLE C-factor Coefficient, Crop Height Factor	X
PARM1501	PARM(62)	Manure Erosion Equation Coefficient	
PARM1501	PARM(68)	Manure Erosion Equation Exponent	
PARM1501	PARM(70)	Microbial Decay Rate Coefficient	X
PARM1501	PARM(76)	Standing Dead fall Rate Coefficient	
PARM1501	PARM(83)	Drainage System Lateral Hydraulic Conductivity Factor	X
PARM1501	PARM(92)	Runoff Volume Adjustment for Direct Link	X
PARM1501	PARM(96)	Soluble Phosphorus Leaching KD Value	X
SUBAREA	DRT	Time for Drainage System to End Plant Stress	

The final automatic calibration included the seven parameters listed in Table 18, where a total of 648 parameter sets were simulated. Model site-weighted calibration statistics were calculated for the seven calibration sites (PAW1, SHE1, SHO1, JBT01, JBT05, JBT11, and M1). The top ~5% of model simulations resulting in the best (lowest) mean absolute error in annual total P (TP MeanAbsError) were identified, resulting in 32 candidate parameters sets. Based on this population of parameter sets, we then wanted to minimize the mean absolute percent bias in average annual total P load (TP-Abs(PBIAS)) across the seven sites. The reason for choosing the lowest average absolute percent bias as opposed to the average percent bias closest to zero was because multiple large negative and positive percent bias values could result in an average percent bias across all sites of close to zero, yet not perform well for any of the sites. Therefore, we ranked the 32 parameters sets from lowest to highest based their average absolute percent bias across all seven sites. The parameter set with the lowest average absolute percent bias in average annual total P was selected as the "best" parameter set for the calibration sites. The APEX parameter vales identified as this "best" parameter set are shown in Table 19.

The "best" parameter set based on the APEX calibration sites was then applied to the remaining 5 validation sites (CHA1, FER1, JBT04, JBT07, and JBT18). The same model performance statistics for average annual flow and total P were then calculated for the validation sites on their own and for the combined set of all calibration and validation sites pooled together. These statistics are summarized in Table 20. The results show that the final global parameterization performs similarly for the calibration sites and the validation sites. For the flow statistics, the validation sites performed modestly better than the calibration sites. The total P percent bias (TP-PBIAS) was negative (-8.06%) for the calibration sites and positive (10.87%) for the validation sites. This indicates that based on this sampling of 12 sites, the overall percent bias could be expected to be closer to zero. This is supported by the percent bias statistic for all sites combined of -0.17%.

Perhaps the one statistic that is most different between the calibration and the validation sites is the total P percent bias (TP-PBIAS). This higher value in the calibration sites is because of a large total P percent bias at the Miner site. A summary of calibration statistics for individual sites is provided in Table 21. Three of the sites have total P percent bias of +/- 10% or less and eight sites have values of +/- 25% or less. Four sites have total P percent bias of more than +/- 50%. The largest outlier is the total P tile load from the M1 site in New York, where model-predicted total P load was 2 times greater than observed total P loads. However, it is important to note that the mean absolute error in total P (TP-MeanAbsError) at the M1 site of 0.09 lbs/acre-yr is less than four of the six other tile drained sites, which range from 0.05 lbs/acre-yr to 0.30 lbs/acre-yr. The largest outlier in flow was surface runoff at CHA1, where model-predicted annual average flow was approximately 63% less than observed.

Table 19. Summary of calibrated APEX parameter values for the global parameter calibration.

Parameter ID	Parameter Definition	Parameter Range	Calibrated Value
LBP	Soluble Phosphorus Runoff Estimate Equation	0,1	1 (Langmuir equation)
ISLF	Slope Length/Steepness Factor	0,1	1 (MUSLE)
IPRK	Soil Water Percolation Method	0,1	0 (original)
DRV	Equation for Water Erosion	0,1,2,3,4,5,6	3 (MUSS)
PARM(8)	Soluble Phosphorus Runoff Coefficient (0.1 m3/t)	10 - 20	10
PARM(20)	Runoff Curve Number Initial Abstraction	0.05 - 0.40	0.2
PARM(23)	Hargreaves PET Equation Coefficient	0.0023 - 0.0032	0.0032
PARM(29)	Biological Mixing Efficiency	0.1 - 0.5	0.4
PARM(46)	RUSLE C-factor Coefficient, Residue Function Factor	0.5 - 1.5	1.5
PARM(47)	RUSLE C-factor Coefficient, Crop Height Factor	0.1 - 1.5	0.1
PARM(62)	Manure Erosion Equation Coefficient	0.1 - 0.5	0.25
PARM(68)	Manure Erosion Equation Exponent	0.1 - 1.0	0.5
PARM(70)	Microbial Decay Rate Coefficient	0.5 - 1.5	1.4
PARM(76)	Standing Dead fall Rate Coefficient	0.0001 - 0.1	0.01
PARM(83)	Drainage System Lateral Hydraulic Conductivity Factor	0.1 - 10.0	0.75
PARM(92)	Runoff Volume Adjustment for Direct Link	0.1 - 2.0	0.85
PARM(96)	Soluble Phosphorus Leaching KD Value	1.0 - 15	1
DRT	Time for Drainage System to End Plant Stress (days)	0 - 365	2 - 4

Table 20. Summary of calibration statistics for calibration sites, validation sites, and all sites.

Statistic	Calibration Sites	Validation Sites	All Sites Combined
Flow-PBIAS (%)	-24.40	-2.82	-15.41
Flow-Abs(PBIAS) (%)	31.99	23.47	28.45
Flow MeanAbsError (mm/yr)	41.58	41.55	41.57
TP-PBIAS (%)	-8.06	10.87	-0.17
TP-Abs(PBIAS) (%)	44.31	26.08	36.71
TP MeanAbsError (lbs/acre-yr)	0.13	0.19	0.16

Table 21. Summary of individual site calibration statistics, global parameterization.

Site	Flow-PBIAS (%)	Flow MeanAbsError (mm/yr)	TP-PBIAS (%)	TP MeanAbsError (lbs/acre-yr)
CHA1-Surface	-63.00	100.73	-23.40	0.65
FER1-Surface	-3.15	19.79	24.82	0.14
JBT01-Tile	-37.88	80.66	-54.23	0.30
JBT04-Tile	15.83	20.22	-14.63	0.05
JBT05-Tile	26.55	32.75	-47.98	0.11
JBT07-Tile	35.53	30.81	65.55	0.12
JBT11-Tile	-27.74	41.80	8.20	0.07
JBT18-Tile	0.70	36.20	2.01	0.11
PAW1-Surface	-28.82	25.29	-5.10	0.10
SHE1-Surface	-45.69	58.42	14.38	0.23
SHO1-Surface	-32.71	16.67	-67.90	0.14
M1-Tile	-46.46	58.44	208.62	0.09
M1-Surface	-2.54	11.25	-16.12	0.11

Additional evaluation of time series plots of the observed versus model-predicted annual flows and total P loads are provided for all 12 sites in Appendix A. A summary plot showing the average annual model-predicted and average annual observed total P load is shown in Figure 2 below. Overall, the APEX models with the global parameterization show strong agreement in the variability in the magnitudes of the total P loads across the 12 sites.

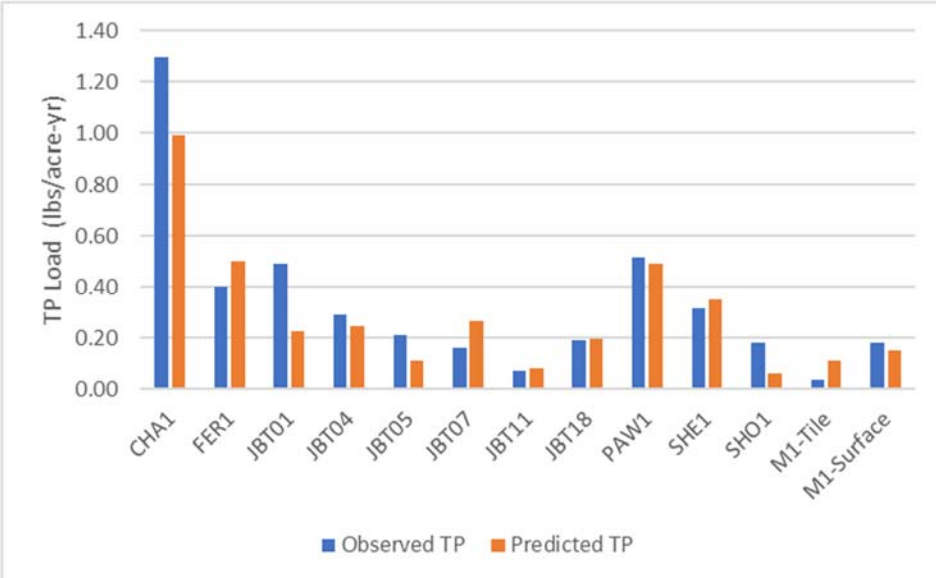

Figure 2. Observed (blue) and model-predicted (orange) average annual total P loads, where predicted loads are based on the global parameter set and representative soils.

The APEX model's predictions of the variability in average annual total P loads among the 12 surface monitoring and tile monitoring sites is further demonstrated by the scatter plot of the observed versus model-predicted average annual total P loads (with both tile and surface for M1) provided in Figure 3. The coefficient of determination (r^2) is 0.87 and the slope of the regression line is 0.73. This indicates that the global parameterization of APEX, applied consistently across surface runoff and tile drained sites, captures the trends in total P loads across sites with varying crop rotations and soils, and has limited bias in predicting total P loads.

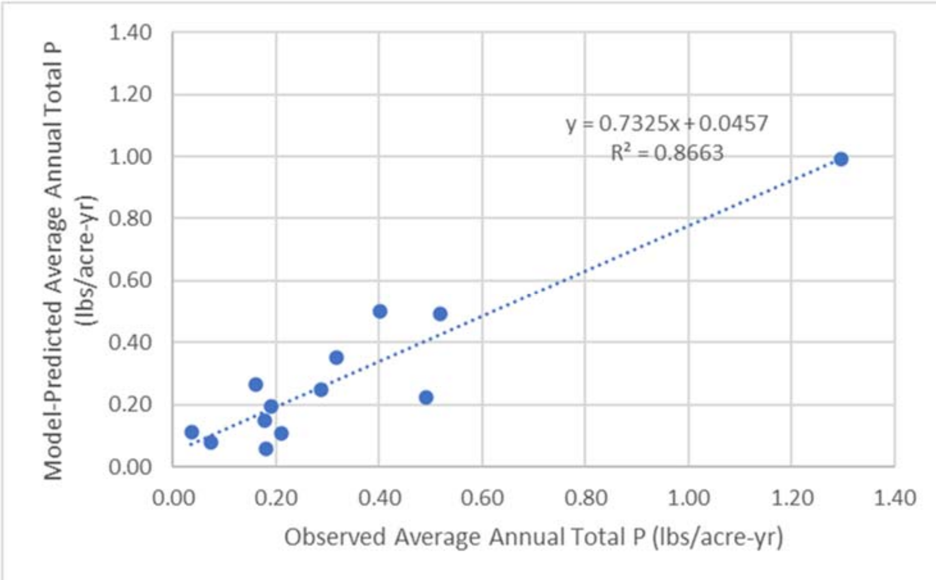

Figure 3. Observed versus model-predicted average annual total P for all 12 sites using global parameterization.

The model performance statistics for the group of independent calibration sites and validation sites showed that the selected parameter set performed similarly across both groups. Considered as a single group, the overall percent bias in average annual total P loads was near zero, with a mean absolute error in average total P load of 0.16 lbs/acre-yr. Given the purpose of this APEX model calibration, the simulation of average annual total P loads, the calibration and validation statistics and the plots of model-predicted versus observed annual P loads demonstrates that the APEX model with a global parameterization reasonably reflects the observations in the edge-of-field surface monitoring and tile drained monitoring sites assessed.

3.2.3.4. Monte Carlo Analysis of Soils Parameter Uncertainty with Global Parameterization

A Monte Carlo analysis was conducted to evaluate APEX model simulations for all 12 sites with respect to the uncertainty inherently in the raw soils data from the NRCS SSURGO database, plus uncertainty in the tile drainage efficiency. The SSURGO database provides a "low," "representative," and "high" value for many of the parameters that describe soil horizon properties. In the absence of site-specific data, the "representative" values are chosen for parameterizing APEX in Farm-PREP. However, the actual soil properties for a given site are not precisely known. This Monte Carlo analysis focused on five soil parameters that vary with horizon in the soil profile: bulk density, sand content, silt content, organic carbon content, and saturated conductivity. Each of these five parameters were varied across their range from the SSURGO "low" to "high" values. Each individual parameter was adjusted in the same direction and the same amount for all soil horizons simultaneously. For example, when the SSURGO "low" value was selected for bulk density, the "low" value was assumed for all horizons. The APEX drainage time to relieve plant stress parameter (for tile drained sites) was also included in this Monte Carlo analysis, as this parameter is difficult to estimate for a given site and has significant dependency on site-specific soil properties. The number of simulations included for each site was partly dependent upon the SSURGO soils data for the site but was approximately 700 simulations for surface edge-of-field sites and 2700 simulations for sites with tile drainage.

The results of the Monte Carlo analysis produced several outputs of interest. First, the analysis provided APEX parameter sets that fall within the range of reported soils data from which a potential improvement over the "global parameterization" could be selected. Second, the analysis produced cumulative distributions of predicted average annual total P load, which we could compare against the observed average annual total P load. This allows for determination of whether the uncertainty in soils inputs, in combination with the global parameterization identified, explains the deviations between the APEX model simulations and the measured total P loads.

An update to Table 21, based on "best" soils parameter sets for each site extracted from the Monte Carlo analysis, is provided in Table 22. With the updated parameterizations, nine of the sites have total P percent bias of +/- 10% or less, with 11 sites value of +/- 25% or less. One site has a total P percent bias of more than +/- 50% (M1 tile). A plot showing the observed and model-predicted average annual total P load based on the best soils parameterization for each site is shown in Figure 4.

Table 22. Summary of individual site calibration statistics, global parameterization with "best" soils parameters.

Site	Flow-PBIAS (%)	Flow MeanAbsError (mm/yr)	TP-PBIAS (%)	TP MeanAbsError (lbs/acre-yr)
CHA1-Surface	-61.71	98.66	-9.83	0.65
FER1-Surface	-5.14	19.73	-1.87	0.12
JBT01-Tile	-18.40	41.23	-24.58	0.27
JBT04-Tile	-1.67	2.13	-4.89	0.02
JBT05-Tile	48.63	59.98	-5.85	0.02
JBT07-Tile	-7.71	6.73	4.37	0.04
JBT11-Tile	-12.55	18.91	-1.21	0.06
JBT18-Tile	-5.65	25.23	-4.75	0.08
PAW1-Surface	-27.86	24.45	4.64	0.05
SHE1-Surface	-31.59	43.19	-19.41	0.14
SHO1-Surface	-21.23	12.93	-48.83	0.10
M1-Tile	-57.97	70.97	77.60	0.06
M1-Surface	14.35	15.60	-0.20	0.13

An updated scatter plot of observed versus model-predicted average annual total P loads for all 12 sites, based on the updated soils parameterization for each site (Figure 5). With the selection of more appropriate soils parameters for each site, the r^2 is 0.98 and the slope of the regression line is 0.90. Acknowledging the uncertainty in the soil properties on a site by site basis allows for refinement in the APEX model simulations and predictions that are closer to observed values. Annual time series plots of flow and total P load for all 12 sites based on the updated soils parameters and the global calibration are provided in Appendix B.

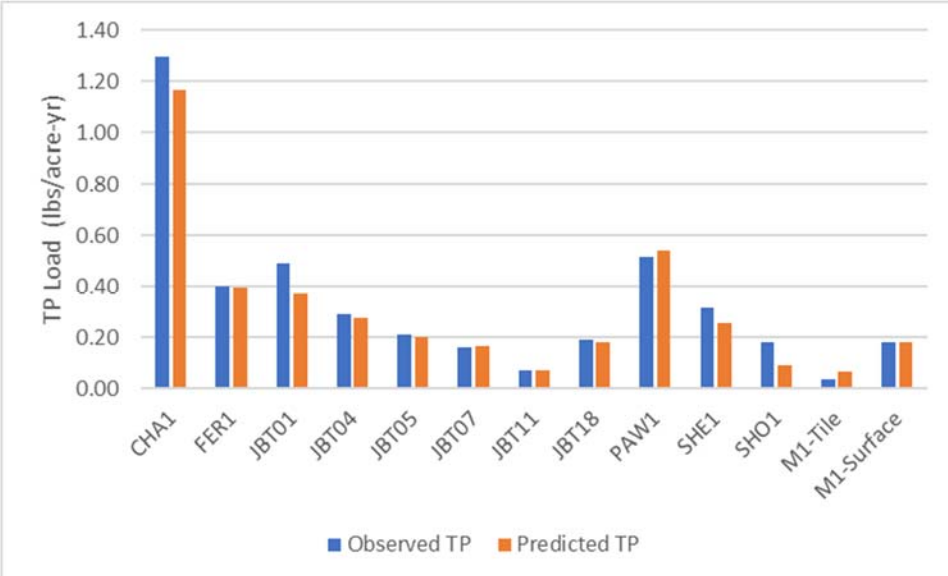

Figure 4. Observed (blue) and model-predicted (orange) average annual total P loads, where predicted loads are based on the global parameter set and "best" soils parameters.

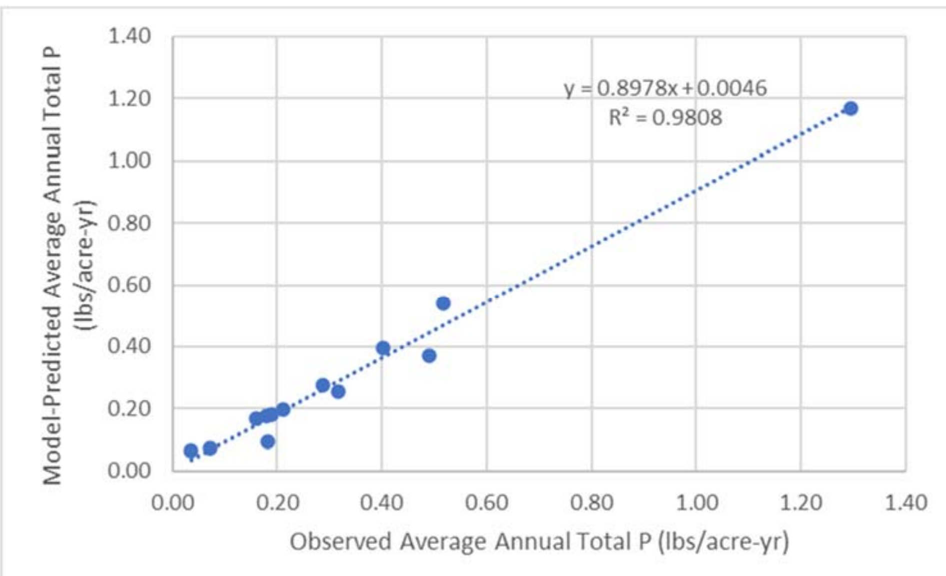

Figure 5. Observed versus model-predicted average annual total P for all 12 sites using global parameterization with "best" soils parameters.

Cumulative distributions of average annual total P load were generated and converted to a percent bias representation. Cumulative distribution plots for each site are provided in Appendix C. The confidence intervals of these cumulative distributions are summarized in Table 23 below. The nine sites highlighted in Table 23 are those where the inner 90% of simulations (90% confidence interval) include a soils parametrization that resulted in a percent bias in average annual total P load of near zero. Of the other four sites where the 90% confidence interval does not include a zero-bias simulation, JBT07 includes a simulation with total P percent bias of near zero within the full population of simulations.

Table 23. Confidence intervals of total P percent bias from global parameterization soils uncertainty Monte Carlo analysis.

	Percent Bias in Average Annual Total P load (%)		
Site	**50% Confidence Interval**	**75% Confidence Interval**	**90% Confidence Interval**
CHA1-Surface	-39.4 - -24.0	-45.2 - -19.0	-50.2 - -13.2
FER1-Surface	-34.5 - 31.7	-46.2 - 59.5	-55.8 - 82.8
JBT01-Tile	-54.4 - 42.5	-59.5 - 38.6	-64.9 - -31.2
JBT04-Tile	-27.7 - 3.5	-37.3 - 11.7	-45.3 - 26.5
JBT05-Tile	-59.6 - -19.2	-66.2 - -4.1	-68.7 - 7.4
JBT07-Tile	22.0 - 85.5	10.1 - 103.4	1.7 - 121.5
JBT11-Tile	-3.2 - 12.5	-13.7 - 19.4	-24.5 - 24.2
JBT18-Tile	-11.5 - 37.0	-18.0 - 56.1	-23.2 - 70.0
PAW1-Surface	-23.0 - 33.2	-36.5 - 52.4	-44.8 - 74.7
SHE1-Surface	-9.3 - 47.3	-18.9 - 66.6	-26.9 - 89.9
SHO1-Surface	-73.5 - -65.6	-76.5 - -62.6	-83.8 - -57.9
M1-Tile	211.2 - 1835.6	146.4 – 8360	92.88 - 11723
M1-Surface	-26.7 - 66.2	-50.3 - 270.6	-62.8 - 980.7

3.2.3.5. Automatic Calibration of Site-Specific Parameterization

The same subset of seven APEX global parameters calibrated in Step 3 were calibrated for each of the 12 sites independently, while keeping the soils parameters at their SSURGO representative values. For each site, a parameter set was chosen that minimized total flow bias and total P bias. The average annual total P load results from the simulations for each site are shown in Figure 6 and Figure 7. The r^2 and the slope of the regression line (0.95 and 0.91 respectively) are an improvement over the global parameterization with "representative" soil parameters (Step 3), which is expected. These results from the site-specific parameterization are also an improvement over the global calibration with "best" soil parameters from the Monte Carlo analysis (Step 4). This is notable, as it indicates that refining these relatively few global parameters for each site can lead to a similar improvement in model performance to that based on adjustment of soil properties within their defined range in the NRCS SSURGO database. Time series plots of flow and total P for each site based on the site-specific parameterization and representative soils parameters are provided in Appendix D.

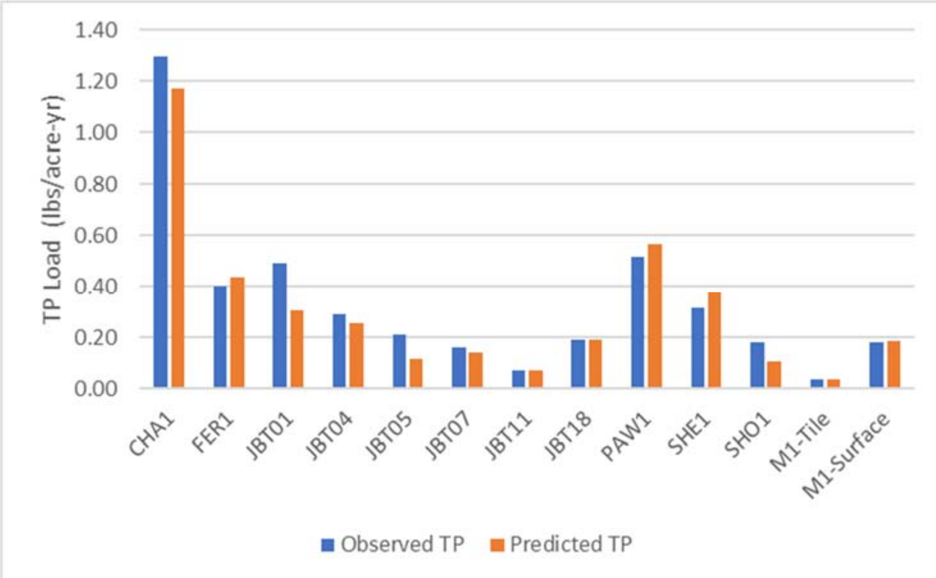

Figure 6. Observed (blue) and model-predicted (orange) average annual total P loads, where predicted loads are based on the site-specific parameter set and representative soils parameters.

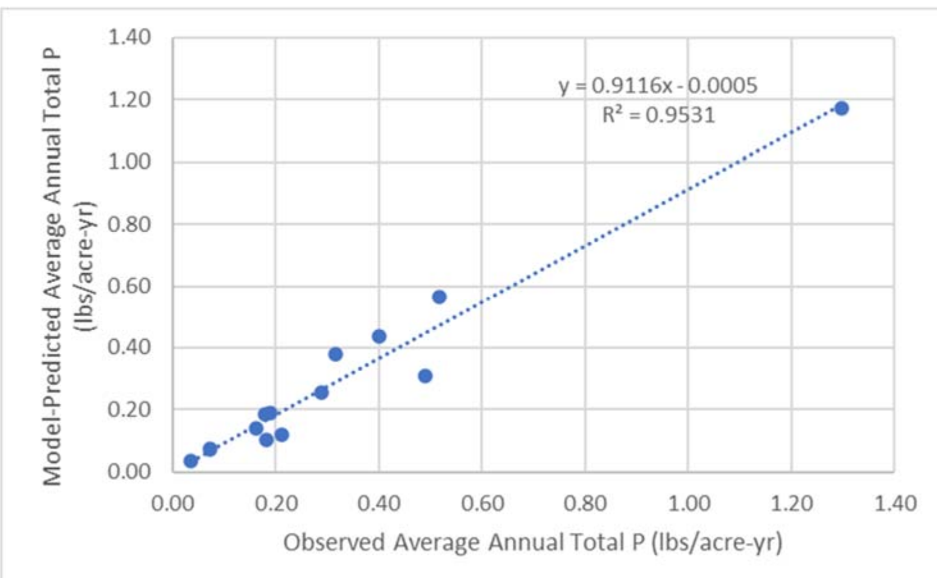

Figure 7. Observed versus model-predicted average annual total P for all 12 sites using site-specific parameterization with representative soils parameters.

3.2.3.6. Monte Carlo Analysis of Soils Parameter Uncertainty with Site-Specific Parameterization

A Monte Carlo analysis of soil properties, analogous as to what was conducted in Step 4 with the global parameterization, was conducted using the site-specific calibration from Step 5. The average annual total P load results from the simulations using the most appropriate soil parameters for each site are shown in Figure 8 and Figure 9. The r^2 and the slope of the regression line in Figure 9 (0.99 and 0.95 respectively) indicate that these model simulations, based on a limited site-specific calibration (only seven parameters) and soil properties that fall within the reported range for each site, result in very high performance of the APEX model in simulating average annual total P loads. Annual time series plots of flow and total P for each site based on the site-specific parameterization and most appropriate soils parameters are provided in Appendix E.

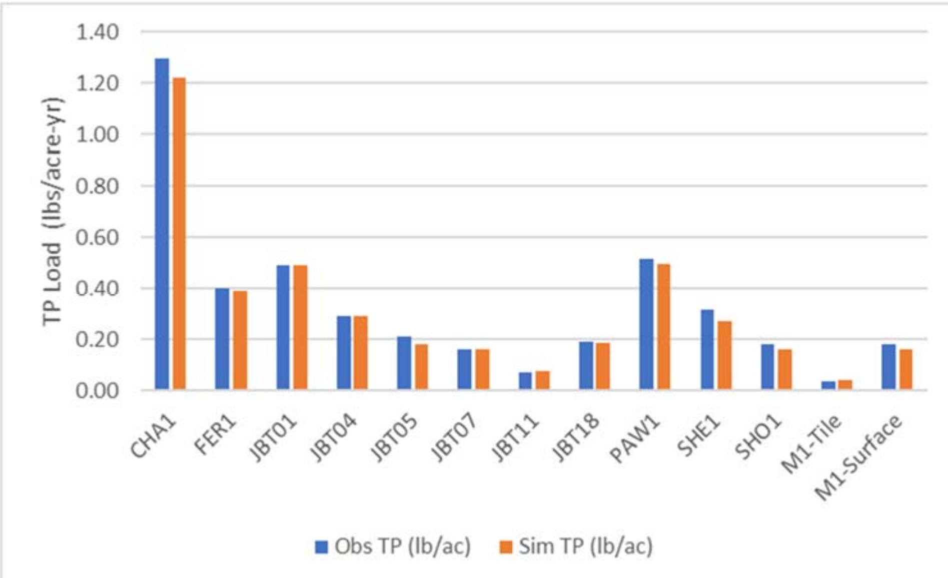

Figure 8. Observed (blue) and model-predicted (orange) average annual total P loads, where predicted loads are based on the site-specific parameter set and "best" soils parameters.

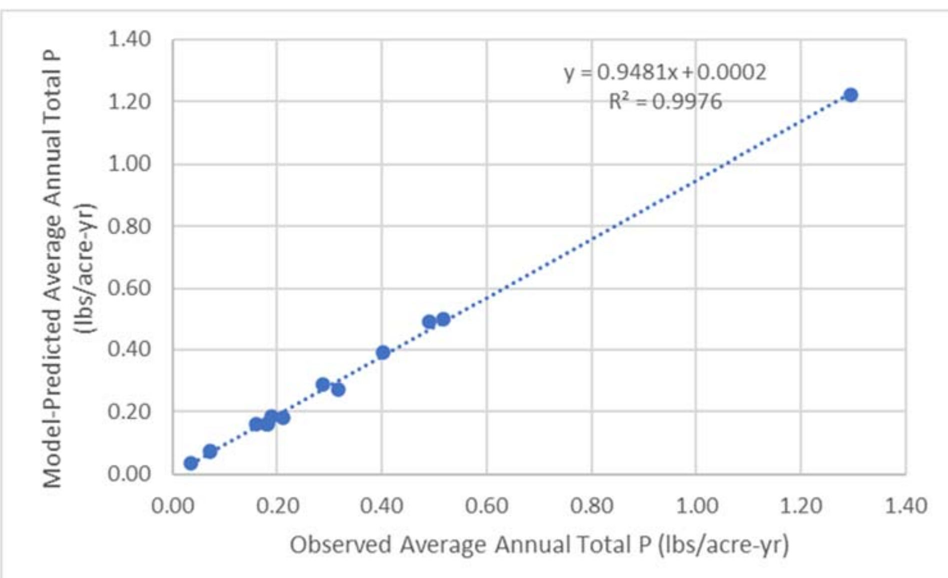

Figure 9. Observed versus model-predicted average annual total P for all 12 sites using site-specific parameterization with "best" soils parameters.

3.2.3.7. APEX Calibration Summary

The calibration and validation effort conducted for the 13 monitoring sites (two from the Miner site) showed that APEX could reasonably simulate average annual surface runoff and tile P loads using a global parameterization and representative soil properties for each site. The level of model bias in annual average P load predictions two thirds of the sites was less than +/-25%, which varied between over and under prediction, with the average bias for all 13 sites of less than 1%. The average annual absolute error in average annual P load predictions across all 13 monitoring sites was 0.16 lbs/acre-yr. The model performance was similar for seven calibration sites and the five independent validation sites. The Monte Carlo analysis conducted for five soil properties, using the global parameterization as a baseline, showed that further improvements in APEX simulations are achievable when selecting a preferable set of soil properties that fall within their ranges provided in the source SSURGO database. The Monte Carlo analysis also showed that for eight of the 13 sites, the observed average annual P load fell within the 90% confidence interval of Monte Carlo simulation predictions. The site-specific calibrations, as well as the Monte Carlo analysis based on the site-specific calibrations, demonstrated that when the global parameters are further refined to an individual site, APEX model simulations can be further improved.

The calibration/validation and Monte Carlo analyses have resulted in a better understanding of the ability of the APEX model to predict surface and tile P loads. The effort has also resulted in a global parameterization that minimizes the bias in average annual P loads across a range of site conditions, crop rotations, and geography within the Lake Champlain Basin. These analyses have also suggested that refinement in soil properties (based on site-specific measurements) and associated model inputs has the potential to improve APEX model simulations of both tile P loads and surface runoff P loads.

3.3. Assessment of Management Scenarios for Innovative Manure Management

3.3.1. Background

This analysis was conducted subsequent and independent to the calibration/validation exercise and was designed to use APEX to assess the potential for reducing P loads by simulating the implementation of best conservation practices and manure management technologies. Manure is often applied at higher rates to fields close to the dairy milking facility and storage pit because the nutrient density is low and transporting significant distances is cost prohibitive. The benefit tied to the adoption of manure management technologies is the generation of new manure-based fertilizer products that are both storable and transportable allowing for placement where and when the nutrients are needed, and for allowing the export of these products to agricultural land that traditionally has not benefited from dairy manure. Two manure management technologies were chosen to simulate in APEX: dissolved air floatation (DAF) and evaporation. A brief description of these technologies is provided below, and further details can be found in the Newtrient Technology catalog for evaporation: https://www.newtrient.com/Catalog/Technology-Catalog/S/Sedron-Agriculture-Thermal-Processing and for DAF https://www.newtrient.com/Catalog/Technology-Catalog/D/DVO-Inc-Phosphorus-Recovery.

DAF systems are part of a class of technologies (fine solids flocculation systems) in which chemical inputs are introduced to aggregate small colloidal and suspended solids into larger flocs for separation, dewatering, and removal into a stackable pile. The organic N and total P fraction preferentially separates with the fine solids in the wastewater, allowing for significant partitioning of these nutrients into a denser form. In general, the partitioned solid fraction is dewatered using mechanical solid-liquid separation and can be further processed in a dryer to produce DAF solids. The products of these technology include a coarse fiber product, DAF solids, and a DAF 'tea' liquid. Approximately 75% of the organic N and total P partitions with the solids fraction with the balance in the tea water.

The evaporation system represents a complete manure treatment solution, where liquid manure inputs are separated into solid and water components that are additionally heated, sterilized, and distilled. The products of this technology are a coarse fiber product, a dry solid manure product, ammonia (as a liquid), and a 'clean' water (that can be treated to desired quality standards for reuse such as for environmental release, irrigation, reclaimed water, or wastewater treatment discharge). The coarse fiber and dry solids products contain P (most of which is in the dry solids), while the ammonia and water products contain no P but do contain nitrogen (N) that can be used to supplement commercial N products. The substitution of commercial N from onsite manure sources is a benefit of this technology, but simulations presented here do not include optimization of N applications or representation of reducing use of commercial N fertilizers.

3.3.2. Modeling Approach

Three of the previously calibrated tile drained sites, one edge-of-field site, and the Miner site were chosen for this exercise (JBT01, JBT11, JBT18, PAW1, and M1). These sites were selected to include a range of crop types and tile/surface P loads. A baseline management schedule was developed for each site using Farm-PREP default operations for each of the rotations represented in the chosen sites (corn/soybean, continuous alfalfa, corn/hay, continuous corn, and continuous corn, respectively). Note, the operations used for these scenarios were generalized and therefore different than the site-specific operations used in the calibration/validation exercise described in Section 3.2. Simulations were conducted using a 20-year time series (1996-2016) from the nearest Farm-PREP weather station. For tile drained sites as well as the Miner site, the closest weather station was the St Albans Bay, VT station (USC00437026) and for PAW1, this was the Wells, VT station (USC00438905).

The analysis was completed by simulating the implementation of on-field conservation practices and manure management technologies independently, and then simulating the implementation of the conservation practices in conjunction with each technology. The following on-field conservation practices were included in this analysis: no-till, cover cropping (cover crop plant date of October 1st), manure injection and the combination of no-till and cover cropping. Table 24 shows the scenarios that were the basis for this evaluation of manure management technologies.

Table 24. Description of scenarios conducted for assessment of manure management.

Field	Crop/ Rotation	Technology	Agricultural Conservation Practice Simulated				
			No Practices	**No-till**	**Cover Crop**	**Manure Injection**	**No-till + Cover Crop**
JBT01	Corn/ soybean	None					
		DAF				N/A[1]	
		Evaporation				N/A	
JBT11	Continuous hay (alfalfa)	None		N/A	N/A		N/A
		DAF		N/A	N/A	N/A	N/A
		Evaporation		N/A	N/A	[2]	N/A
JBT18	Corn/hay	None					
		DAF				N/A	
		Evaporation				N/A	
M1	Continuous corn	None					
		DAF				N/A	
		Evaporation				N/A	
PAW1	Continuous corn	None					
		DAF				N/A	
		Evaporation				N/A	

[1]N/A indicates scenarios that were not simulated because it was not practical for the crop rotation and/or technology combination.
[2] This scenario represents injection of dry solids, produced from evaporation technology, for which equipment is potentially being developed.

The APEX model that was the result of the calibrated global parameter set and best performing site-specific soils (Section 3.2.3) for each site was used as the basis for setting up these simulations. Operations schedules were then modified from site-specific management practices to reflect 'standard' practices and timing of practices associated with each crop/rotation shown above. The idea behind standardizing the operations schedules was to allow for evaluating the impacts of just manure technologies (DAF or evaporation) and conservation practices on P loads from a suite of representative sites. These were then further modified to reflect the use of DAF or evaporation technologies (including modified timings and application of manure products as opposed to the standard liquid dairy manure used in the no technology simulations), and/or to reflect the implementation of specified conservation practices. DAF and evaporation technologies were applied only in the spring in comparison to the no technology baseline in which 25% of annual manure application were placed in the spring and the remaining 75% in the fall. No technology scenarios used applications of VTP2O5-LowDM (liquid dairy manure, Section 3.2.1.3) where manure technology products were used in DAF and evaporation technology scenarios.

Manure technology products were assumed to be created by applying each technology to VTP2O5-LowDM manure. Nutrient fractions for each product were determined based on guidance provided by Newtrient based on their experience with DAF and evaporation technologies (see Table 25). The fraction of organic carbon was unknown for these technology products; solid or semi-solid manure products were assigned 0.5863 (same as VTP2O5-LowDM) and liquid products were assigned a nominal value of 0.0500.

Table 25. Nutrient fractions for dissolved air floatation (DAF) and evaporation manure products.

Fertilizer	Mineral N (fraction)	Mineral P (fraction)	Mineral K (fraction)	Organic N (fraction)	Organic P (fraction)	Ammonia N (fraction of mineral N that is in form of ammonia)	Organic C (fraction)
DAF Tea	0.1205	0.0039	0.3083	0.0558	0.0021	1.0000	0.0500
DAF Coarse Fiber	0.0019	0.0022	0.0048	0.0177	0.0012	1.0000	0.5863
DAF Solids	0.0019	0.0072	0.0048	0.0275	0.0039	1.0000	0.5863
Evaporation Coarse Fiber	0.0019	0.0022	0.0048	0.0177	0.0012	1.0000	0.5863
Evaporation Solids	0.0001	0.0066	0.0655	0.0332	0.0035	1.0000	0.5863
Evaporation Aqua Ammonia	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0500
Evaporation 'Clean' Water	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0500

3.3.2.1. Optimal P Soils

As mentioned in Section 3.3.1, the primary benefit of implementing manure management technologies is the generation of new manure-based products that allow for placement where and when the nutrients are needed. Therefore, the first modification to our standard baseline APEX operations to represent the adoption of these technologies included modified timing and form of manure products relative to liquid dairy manure, with scenarios both with and without specified conservation practices. To focus the analysis on these factors related to implementing technologies, these scenarios were conducted assuming an 'optimal' soil P level. The assumption was that under optimal soil conditions, the same amount of P would be applied regardless of its form (source liquid manure or manure technology product). Each of the scenarios shown in Table 24 was therefore first simulated with optimal soil P values.

Optimal soil P was defined as having a surface soil P content equivalent to a soil test P (based on the Modified Morgan analysis) value of 5 ppm based on the Nutrient Recommendations for Field Crops in Vermont (2018). In APEX simulations, initial soil P below 20 cm is assumed to be half the surface soil P. Initial soluble P concentrations in each soil layer were calculated using the equations described in Section 3.2.1.1. To further target the form of manure, manure applications were made at a rate of 20 lbs/acre P_2O_5 per year, both for the no technology baseline scenario as well as for the scenarios in which DAF and evaporation technologies were applied. For example, when applying the DAF technology on a corn silage rotation, instead of 20 lbs/acre P_2O_5 of 'standard' liquid dairy manure (VTP2O5-LowDM, Section 3.2.1.3) in both the spring and fall, the three DAF manure products (coarse fiber, DAF solids, and DAF 'tea') were applied at a rate equivalent to 20 lbs/acre P_2O_5 but in the spring only.

3.3.2.2. High P Soils

The second set of scenarios to evaluate the P load reduction benefits of on-field conservation practices and manure management technologies was associated with high soil P fields. These scenarios represent a situation where a field, likely in close proximity to the dairy milking facility or manure storage pit, has a high level of soil P associated with manure applications that have historically exceeded crop requirements due to the convenience and lower cost associated with manure application at these sites. These are the situations where manure management technologies offer great potential for reducing manure P input rates to certain fields, and in turn lowering off-site P transport in surface runoff and tile drainage. The increased transportability that these manure products afford in turn allows for nutrient applications to be made to fields that are a further distance (on or off farm) and have not benefited from dairy manure in the past due to high transportation costs associated with liquid dairy manure. Note that this advantage is more relevant at the farm, than field, scale.

For these APEX simulations, scenarios were developed to represent soils with already 'high' soil P levels. High P soils were defined as having a surface soil layer soil test P (based on the Modified Morgan analysis) of 8 ppm (Nutrient Recommendations for Field Crops in Vermont, 2018). In the APEX model, initial soil P below 20 cm is set to half the surface soil P concentration. Initial soluble P concentrations in each soil layer are calculated using the equation presented in Section 3.2.1.1. Each of the scenarios shown in Table 24 was then simulated with high soil P values. A key assumption for these high soil P scenarios is that with technology implemented, a lower volume of manure products may be applied in the simulated scenario relative to the baseline for the field without manure technology implemented. This assumption is based on managing at the farm-level, technology would provide the flexibility to apply manure to different fields on the farm (at a further distance) or off-farm. Thus, with a manure technology adopted, rates of manure product applications can be reduced to only meet crop growth requirements.

In order to dynamically simulate variable application rates of manure products, targeted to meet crop growth demands, the APEX code was modified to dynamically apply manure at a rate that met target residual soil P required to meet plant demands. Thus, if soil P in the plow layer (plow layer depth defined as 6 inches for these simulations) is higher than the target residual soil P, no manure will be applied in that year. However, if the soil P decreases after some number of years to below the target residual soil P level, then manure will be applied at a rate such that soil P does not exceed the target residual P and such that plant demand is met.

In the baseline scenarios (simulating no technology), manure applications were made at a rate of 40 lbs/acre P_2O_5 per year. The assumption was that applications are not being made at rates in accordance with the Nutrient Recommendations for Field Crops in Vermont, thereby contributing to high soil P levels. In the high soil P scenarios where DAF and evaporation technologies are implemented, the APEX dynamically determined the rate at which manure products were applied in years when soil P levels dropped below target levels as measured before annual crop planting. The target soil P levels were set through an evaluation at each site to determine a beginning of growing season soil P concentration needed to ensure an average of less than one day of crop P stress per year over the 20-year simulation.

To gain an overview of the impact of the manure management technology and on-field conservation practices implemented in the described APEX scenarios, average annual P loads (based on 20-year simulations) were calculated and used for initial comparison of scenario results. The average annual P loads were broken up into the tile P, soluble surface P, sediment surface P, and total P components. These average annual P loads where either a manure management technology or on-field conservation practice was assumed were the compared against a "baseline" scenario (i.e., a scenario with no technology or conservation practices) to calculate the percent reduction in the average annual P loads.

3.3.3. Results

3.3.3.1. Optimal P Soils

Table 26 shows the range of P reductions achieved when each conservation practice scenario was compared to the baseline scenario in which no practices were applied (e.g. the no-till DAF scenario was compared to the no practices DAF scenario and the cover crop no technology scenario was compared to the no practices no technology scenario). Scenarios that included the simulation of on-field conservation practices resulted in total P reductions ranging from none (-0.7%) to 44.1% across the five sites and the three different manure scenarios. It should also be noted that these five sites included a soybean/corn rotation (JBT01), a permanent hay rotation (JBT11), two permanent corn rotations (M1 and PAW1), and a corn/hay rotation (JBT18). The corresponding ranges in average annual P loads are provided in Table 27, which shows how the magnitude of the P load components can vary, with sediment P generally the highest component, followed by tile P and soluble P. As seen in Table 26, the effectiveness of each conservation practice varied across the sites and scenarios simulated. For example, cover cropping resulted in a sediment P reduction ranging from 1.6% to 22.4%. A summary of the median P load reductions, provided in Figure 10, shows that reductions in soluble P were greatest, followed by sediment and the tile P load. Of the conservation practices evaluated, the combination cover crop and no-till was the most effective a reducing P, followed by no-till, cover crop on its own, and manure injection.

Table 26. Range of percent P reductions in manure management scenarios resulting from APEX simulation of conservation practices on fields with optimal P soils (including no technology, dissolved air floatation (DAF), and evaporation technology scenarios).

Field Practice	Tile P (% Reduction)			Soluble Surface P (% Reduction)			Sediment Surface P (% Reduction)			Total P (% Reduction)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
Manure Injection	-2.2	0.0	0.1	-1.2	0.5	2.2	0.0	1.3	4.1	-0.7	0.9	2.3
No-till	4.8	8.6	29.5	14.8	34.5	60.7	-2.9	15.4	31.9	1.7	17.0	26.7
Cover Crop	-4.4	2.8	4.2	23.5	39.7	51.4	1.6	7.8	22.4	2.1	7.3	20.5
Combined Cover Crop and No-Till	3.5	20.5	32.3	46.0	59.8	77.0	14.1	31.2	45.4	11.4	32.1	44.1

Table 27. Range of P loads in manure management scenarios resulting from APEX simulation of conservation practices on fields with optimal P soils and (including no technology, dissolved air floatation (DAF), and evaporation technology scenarios).

Field Practice	Tile P (lbs/acre-yr)			Soluble Surface P (lbs/acre-yr)			Sediment Surface P (lbs/acre-yr)			Total P (lbs/acre-yr)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
None	0.020	0.099	0.169	0.003	0.007	0.075	0.033	0.414	3.390	0.056	0.547	3.464
Manure Injection	0.020	0.079	0.168	0.003	0.008	0.075	0.031	0.406	3.361	0.054	0.559	3.436
No-till	0.055	0.115	0.157	0.003	0.005	0.054	0.293	0.357	2.943	0.413	0.457	2.997
Cover Crop	0.075	0.121	0.174	0.003	0.005	0.037	0.268	0.406	3.143	0.445	0.514	3.179
Combined Cover Crop and No-Till	0.053	0.098	0.160	0.002	0.004	0.025	0.246	0.295	2.235	0.349	0.404	2.261

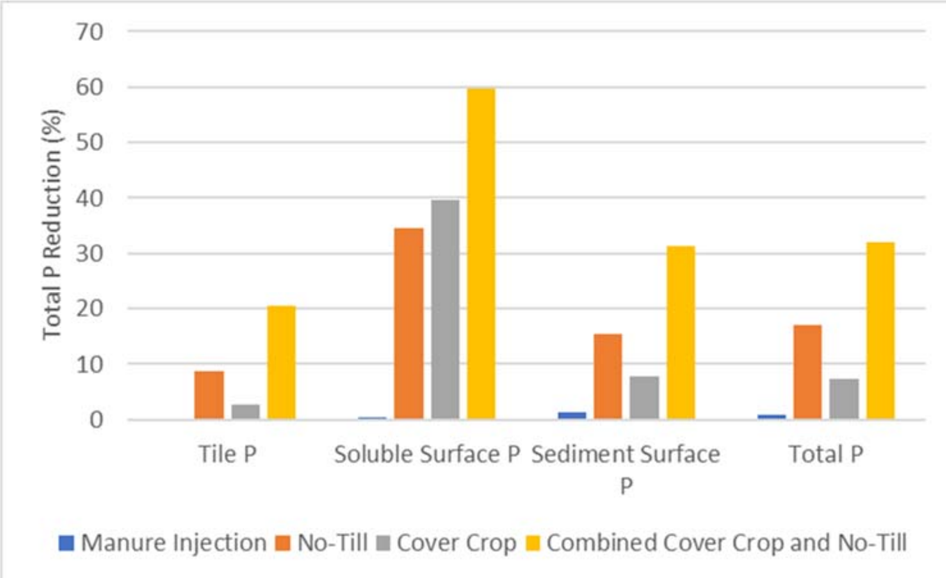

Figure 10. Median reduction in total P load by conservation practice from APEX simulation of Conservation Practices on fields with optimal P soils (including no technology, DAF, and evaporation technology scenarios).

Table 28 shows the range of P reductions achieved across all sites and conservation practices when each manure management technology simulation was compared to the corresponding run with no technology implemented (e.g. the no-till DAF scenario was compared to the no-till no technology scenario). The two technologies resulted in similar predicted P load reductions when compared to a baseline scenario with no manure technology; total P ranged from a P increase of 3.7% to a 12.4% P reduction across the five sites and the four conservation practices simulated. The corresponding ranges in average annual P loads are provided in Table 29, which shows how the magnitude of the P load components can vary, with sediment P generally the highest component, followed by tile P and soluble P. As noted, the effectiveness of each of the two manure technologies on reducing P loads was similar, however the P load reduction effectiveness varied depending upon the P component. A summary of the median P load reductions, provided in Figure 11, shows that reductions in soluble P load were greatest, followed by sediment P, with resulted in a small increase in tile P load.

While manure injection was not expected to have a significant impact on tile P, higher P reduction in surface runoff was expected. The minimal reduction seen in modeling results was thought to be due to the interaction occurring between the soil layer where manure is injected, the mixing of the upper soil layers due to tillage, and the interaction or runoff and erosion with the surface soil layer. Given the unexpected outcome, a review of field data measurements of P load reductions from manure injection practices will be conducted and potential updates to the APEX model and/or parameterization may be required.

Table 28. Range in percent P reductions in manure management scenarios resulting from APEX simulation of manure technologies on fields with optimal P soils.

Manure Technology	Tile P (% Reduction)			Soluble Surface P (% Reduction)			Sediment Surface P (% Reduction)			Total P (% Reduction)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
Dissolved Air Floatation (DAF)	-5.8	-2.2	2.4	0.2	27.7	45.7	-9.8	7.0	16.7	-5.7	5.6	12.4
Evaporation	-4.2	-0.6	1.6	1.4	27.6	45.8	-6.6	7.3	16.5	-3.7	5.6	12.2

Table 29. Range in P loads in manure management scenarios resulting from APEX simulation of manure technologies on fields with optimal P soils.

Manure Technology	Tile P (lbs/acre-yr)			Soluble Surface P (lbs/acre-yr)			Sediment Surface P (lbs/acre-yr)			Total P (lbs/acre-yr)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
None	0.020	0.112	0.172	0.002	0.007	0.075	0.031	0.418	3.390	0.054	0.525	3.464
Dissolved Air Floatation (DAF)	0.020	0.118	0.174	0.002	0.005	0.066	0.036	0.382	3.186	0.059	0.462	3.251
Evaporation	0.020	0.107	0.173	0.002	0.004	0.065	0.033	0.341	3.194	0.056	0.460	3.259

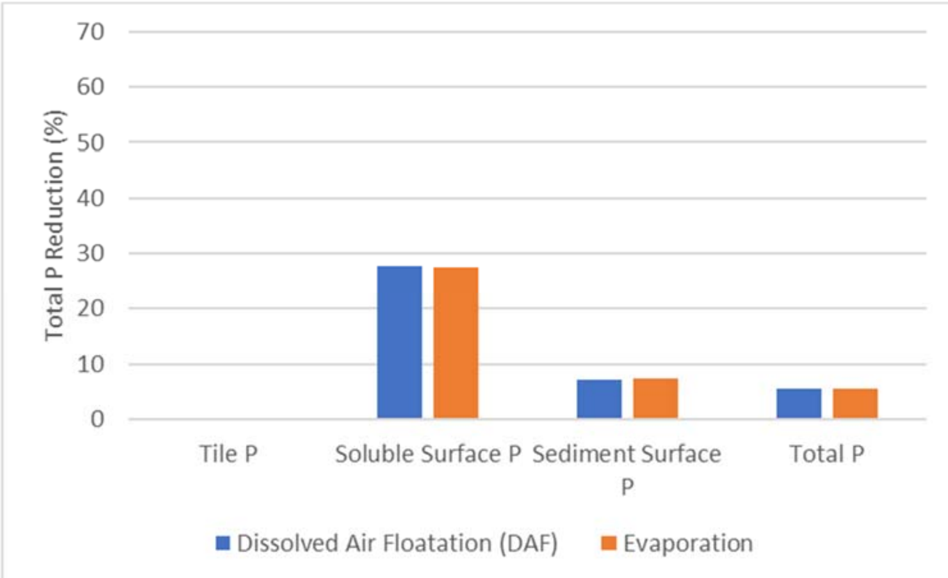

Figure 11. Median reduction in total P load by manure technology resulting from APEX simulation of fields with optimal P soils.

The reductions in P load resulting from the manure technology implementation are largely a result of adjustments to manure product application timing that was simulated in these scenarios. The manure technology scenarios allowed for a more beneficial application timing strategy, with a larger proportion of the manure products applied in the early spring versus the late fall, providing both a better opportunity for crop utilization and lowering high runoff potential in late fall and winter. A secondary factor was the form of the manure products being applied and the allocation of the nutrients in mineral and organic forms, which included application at depth for some manure products.

The results presented in the previously discussed tables and figures are based on average annual P loads over a 20-year simulation. In order to understand how the benefits of implantation of conservation practices and manure technologies may vary over time, we investigated three of the five sites in greater depth (JBT11, JBT18, and M1) and split the simulation results into the years 1 – 10 and years 11 – 20. These results are provided in Table 30 and in Figure 12. In all three sites, reductions in average annual total P load are greater for the years 11 – 20 than for years 1 – 10. Looking at each site independently, the greatest improvement from the second ten-year period compared to the first was observed at JBT01 followed M1 and JBT18. The cumulative distributions shown in Figure 12 show variability in the relative effectiveness of the manure technologies across sites and conservation practices and that the gap between P reduction in the second ten-year period compared to the first ten-year period widens as the overall benefit of the technology increases.

Table 30. Reductions in total P load resulting from manure technology by time for selected sites and practices resulting from APEX simulation of fields with optimal P soils.

Practices	Technology	Reduction in Average Annual Total P Reduction (%)					
		JBT18		M1		JBT01	
		Year 1-10	Year 11 - 20	Year 1-10	Year 11 - 20	Year 1-10	Year 11 - 20
None	Dissolved air floatation (DAF)	5.4	13.1	7.7	17.7	5.5	19.9
None	Evaporation	6.4	12.7	7.6	17.5	5.4	19.3
No-till	Dissolved air floatation (DAF)	5.2	4.9	7.7	7.7	3.5	12.9
No-till	Evaporation	7.6	5.8	7.0	7.7	3.4	13.3
Cover Crop	Dissolved air floatation (DAF)	2.3	6.4	4.4	10.0	3.0	10.2
Cover Crop	Evaporation	3.4	6.6	4.3	9.9	3.2	9.1
Cover Crop/No-till	Dissolved air floatation (DAF)	1.2	1.5	-3.2	-5.6	-1.5	0.1
Cover Crop/No-till	Evaporation	3.7	2.1	-0.4	-1.5	-2.1	1.7
Median		4.5	6.1	5.7	8.8	3.3	11.5

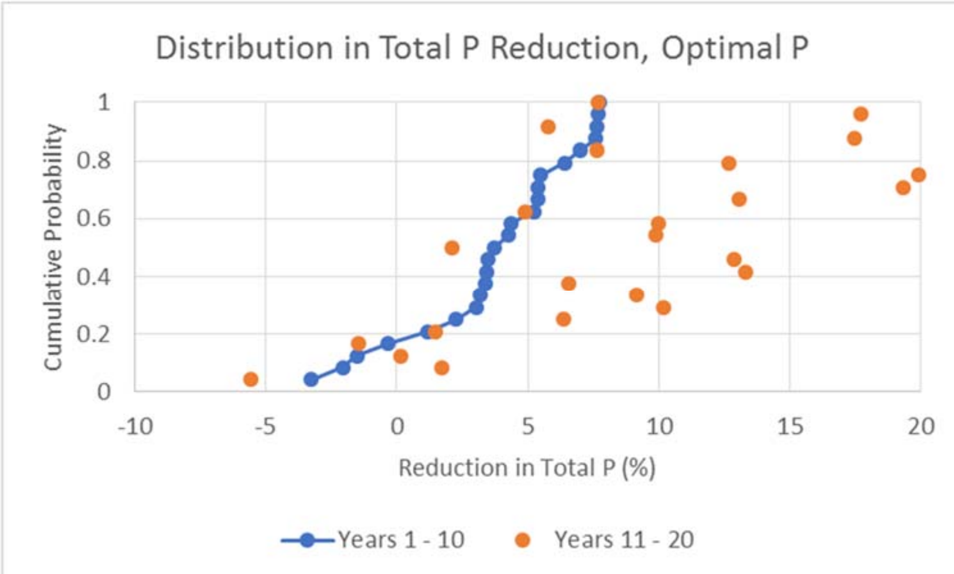

Figure 12. Cumulative distributions of average annual total P load reductions resulting from manure technologies over first ten-year and second ten-year periods. Each point plotted for "Years 11 -20" represents the same manure technology scenario as the corresponding point (i.e., same Cumulative Probability") on the "Years 1 – 10" curve for optimal P scenarios.

Overall, the optimal P scenarios simulated confirmed our previous understanding regarding the effects of on-field conservation practices on reductions in P loads from fields, along with some new insight into the effects of these practices on tile P loads and the effects of manure technology on P loads. Tile P loads often showed modest reductions with the implement of on-field conservation practices, however, showed minimal responses to the adoption of manure technology. Surface P loads, both soluble and sediment, did show modest reductions after the adoption of manure technology, although the degree of impact varied across conservation practices and sites. Overall, with the exception of small increases in tile P loads with manure technology, implementation of the conservation practices and manure technologies assessed, resulted in lower P loads for the evaluated sites.

P loads for each scenario as well as bar charts showing the relative comparison of loads across scenarios for each site independently are provided in Appendix F. Note that for evaluation of trends in the different sources of P (tile, surface, and sediment), the y-axis scale varies in these charts.

3.3.3.2. High P Soils

The same analysis conducted to evaluate on-field conservation practices and manure management technology scenarios for optimal P soils was conducted for soils with high P content. Recall that the high soil P scenarios had both an initial soil P concentration analogous to a "high" classification by UVM Extension, as well as an annual manure application rate that was twice that of the optimal P scenarios. These high soil P scenarios were designed to represent situations where current farm operations resulted in a surplus of manure, leading to over-application on some fields. In these high P scenarios, the simulations of the manure management technologies were different than with the optimal P scenarios. In these high P scenarios, the amount of manure products applied each year was adjusted to meet the crop demand. Meeting crop demand was defined as not inducing more than one day per year of P stress (as determined within APEX model). This approach led to some years where no P was applied, allowing soil P levels to drawdown until additional P was required by the crop. The assumption was that, when manure technology is adopted, flexibility in farm-scale manure management increases, allowing nutrients to be stored and/or transported to other areas as needed. The scenarios simulated in this group of "high P soils" provides additional data on the effectiveness of on-field conservation practices but may be most useful in beginning to understand manure technology benefits for fields and farms facing excessive p and manure challenges.

As with the optimal P scenarios, average annual P loads (based on 20-year simulations) were calculated over a range of conservation practice and manure technology scenarios. The average annual P loads were broken up into the tile P, soluble surface P, sediment surface P, and total P components. These average annual P loads, where either a manure management technology or on-field conservation practice was assumed, were the compared against a "baseline" scenario (i.e., a scenario with no technology or conservation practices) to calculate the percent reduction in the average annual P loads.

Table 31 shows the range of P reductions achieved when each conservation practice scenario was compared to the baseline scenario in which no practices were applied (e.g. the no-till DAF scenario was compared to the no practices DAF scenario and the cover crop no technology scenario was compared to the no practices no technology scenario). Scenarios that included the simulation of on-field conservation practices resulted in total P reductions ranging from none (-5.6%) to 40.2% across the five sites and the three different manure scenarios. It should also be noted that these five sites included a soybean/corn rotation (JBT01), a permanent hay rotation (JBT11), two permanent corn rotations (M1 and PAW1), and a corn/hay rotation (JBT18). The corresponding ranges in average annual P loads are provided in Table 32, which shows how the magnitude of the P load components can vary, with sediment P generally the highest component, followed by tile P and soluble P. As seen in Table 31, the effectiveness of each conservation practice varied across the sites and scenarios simulated. For example, cover cropping resulted in a sediment P reduction from 1.3% to 23.6%. A summary of the median P load reductions, provided in Figure 13, shows that reductions in soluble P were greatest, followed by sediment and the tile P load. Of the conservation practices evaluated, the combination cover crop and no-till was the most effective a reducing P, followed by no-till, cover crop on its own, and manure injection.

Table 31. Range in percent P reductions in manure management scenarios resulting from APEX simulation of conservation practices on fields with high P soils (including no technology, dissolved air floatation (DAF), and evaporation technology scenarios).

Field Practice	Tile P (% Reduction)			Soluble Surface P (% Reduction)			Sediment Surface P (% Reduction)			Total P (% Reduction)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
Manure Injection	-0.4	-0.1	0.0	-0.3	1.1	2.4	0.4	1.9	6.6	0.1	1.4	2.5
No-till	-9.3	6.4	18.6	12.9	33.3	62.1	-3.4	15.1	35.7	-5.6	16.6	25.9
Cover Crop	-7.6	0.8	2.4	20.2	35.0	53.2	1.3	8.4	23.6	0.5	7.7	20.1
Cover Crop/No-till	-10.5	6.3	19.2	36.4	56.8	77.6	14.4	32.4	46.0	4.5	25.6	40.2

Table 32. Range in P loads in manure management scenarios resulting from APEX simulation of conservation practices on fields with high P soils (including no technology, dissolved air floatation (DAF), and evaporation technology scenarios).

Field Practice	Tile P (lbs/acre-yr)			Soluble Surface P (lbs/acre-yr)			Sediment Surface P (lbs/acre-yr)			Total P (lbs/acre-yr)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
None	0.025	0.183	0.357	0.003	0.009	0.237	0.019	0.454	3.884	0.047	0.673	4.121
Manure Injection	0.025	0.151	0.359	0.003	0.022	0.235	0.022	0.486	3.833	0.051	0.784	4.067
No-till	0.094	0.212	0.335	0.003	0.008	0.090	0.290	0.400	3.408	0.496	0.643	3.469
Cover Crop	0.115	0.218	0.367	0.004	0.008	0.111	0.332	0.445	3.581	0.527	0.669	3.692
Cover Crop/No-till	0.093	0.209	0.339	0.002	0.006	0.053	0.292	0.316	2.749	0.408	0.584	2.781

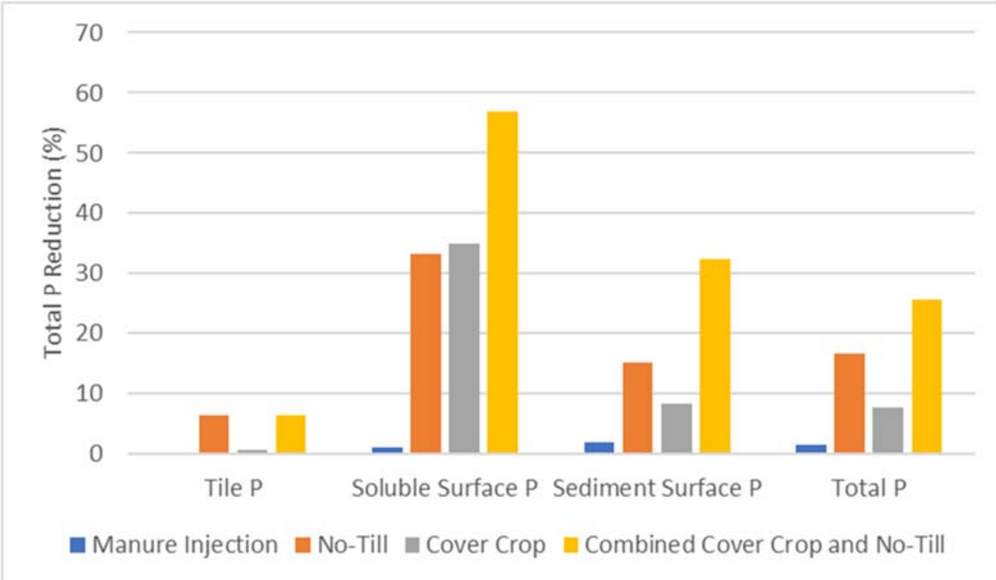

Figure 13. Median reduction in total P load by conservation practice from APEX simulation of conservation practices on fields with high P soils (including no technology, DAF, and evaporation technology scenarios).

Table 33 shows the range of P reductions achieved across all sites and conservation practices when each manure management technology simulation was compared to the corresponding run with no technology implemented (e.g. the no-till DAF scenario was compared to the no-till no technology scenario). The two technologies resulted in similar predicted P load reductions when compared to a baseline scenario with no manure technology; total P ranged from a P increase of 6.1% (reduction of -6.1%) to a 30.3% P reduction across the five sites and the four conservation practices simulated. Note that the scenarios that resulted in an increase in total P load resulting from manure technology were due to MORE manure-based P fertilizer applied in those scenarios to meet plant demand (site PAW1 only). We believe this to be an anomaly, and is due to the "baseline" manure application rate not satisfying plant demand at this site, but decided to keep this PAW1 scenario parameterized as originally designed.

Similar to optimal P soils, for high P soils, minimal reduction in surface P was seen as a result of manure injection. While manure injection was not expected to have a significant impact on tile P, higher P reduction in surface runoff was expected. The minimal reduction seen in modeling results was thought to be a due to the interaction occurring between the soil layer where manure is injected, the mixing of the upper soil layers due to tillage, and the interaction or runoff and erosion with the surface soil layer. Given the unexpected outcome, a review of field data measurements of P load reductions from manure injection practices will be conducted and potential updates to the APEX model and/or parameterization may be required.

Table 33. Range in percent P reductions in manure management resulting from APEX simulation of manure technologies on fields with high P soils.

Manure Technology	Tile P (% Reduction)			Soluble Surface P (% Reduction)			Sediment Surface P (% Reduction)			Total P (% Reduction)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
Dissolved Air Floatation (DAF)	1.0	21.9	28.1	37.7	63.7	84.9	-5.7	10.0	19.4	-1.5	14.1	30.3
Evaporation	1.4	21.8	31.5	40.1	66.1	86.2	-7.1	6.9	21.9	-6.1	15.8	24.7

Table 34. Range in P loads in manure management scenarios resulting from APEX simulation of manure technologies on fields with high P soils.

Manure Technology	Tile P (lbs/acre-yr)			Soluble Surface P (lbs/acre-yr)			Sediment Surface P (lbs/acre-yr)			Total P (lbs/acre-yr)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max
None	0.026	0.268	0.367	0.006	0.019	0.237	0.022	0.467	3.884	0.066	0.768	4.121
Dissolved Air Floatation (DAF)	0.025	0.212	0.292	0.003	0.006	0.086	0.019	0.406	3.495	0.047	0.628	3.581
Evaporation	0.025	0.202	0.278	0.002	0.005	0.090	0.023	0.388	3.586	0.051	0.604	3.676

The corresponding ranges in average annual P loads are provided in Table 34, which shows how the magnitude of the P load components can vary, with sediment P generally the highest component, followed by tile P and soluble P. As noted, the effectiveness of each of the two manure technologies on reducing P loads was similar, however the P reduction effectiveness varied depending upon the P component. A summary of the median P load reductions, provided in Figure 14, shows that reductions in soluble P were greatest, followed by tile P, then sediment P load. Note that this is a different trend than we saw for the optimal P scenarios (see Figure 11) where the reductions in tile P with manure technology were almost none (in fact a small increase for the median reduction). This in an indication that the flexibility to lower manure product application rates on field with high P can have a beneficial impact on the long-term tile drain P loads.

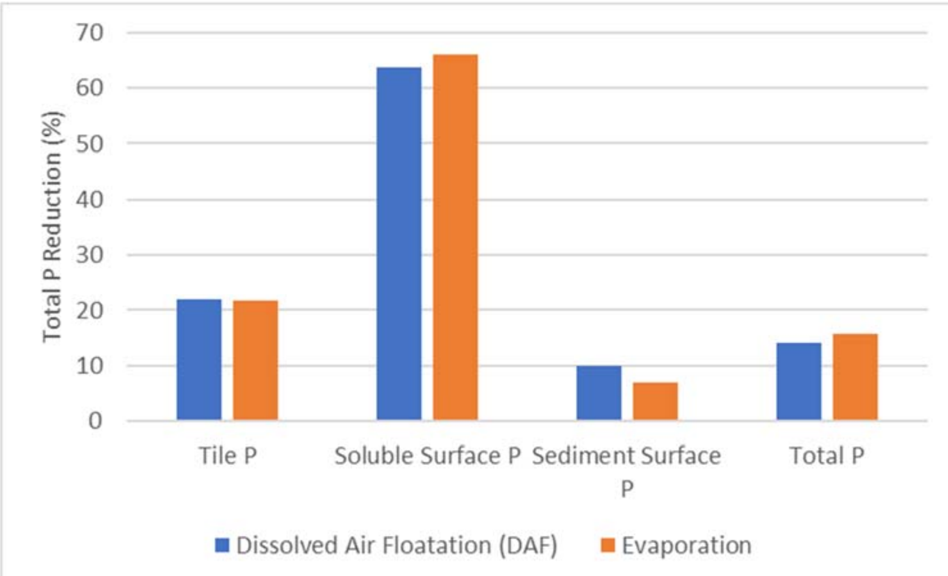

Figure 14. Median reduction in total P load by manure technology resulting from APEX simulations of fields with high P soils.

Based on the 20-year simulations for the high soil P scenarios, we generally saw a higher impact of manure technology on reducing P loads from both tile drain and surface transport. The driving factor for this reduction was the lower rates of P fertilizer applied from the manure products. Of secondary importance were the modification to application timing (focused in the early spring as opposed to split between spring and fall) as well as the form and application methods for the manure products.

As was done for the optimal P scenarios, the reductions in P loads resulting from the adoption of manure management technologies was re-assessed by evaluating the first and second ten-year time periods independently. It is known that drawdown of P from soils excessively rich in P can take multiple years to achieve, thus the greatest benefits to reducing P application rates may be realized further out in the future. The results comparing P load reductions during different time periods for sites JBT01, M1, and JT18 are provided in Table 35 and in Figure 15. In all three sites, reductions in average annual total P load are substantially greater for the years 11 – 20 than for years 1 – 10. Looking at each site independently, the greatest improvement from the second ten-year period compared to the first was observed at JBT01 followed JBT18 and M1. The cumulative distributions shown in Figure 15 show variability in the relative effectiveness of the manure technologies across sites and conservation practices. Contrary to the same cumulative distributions for the optimal P scenarios (Figure 12), that the gap between P reduction in the second ten-year period compared to the first ten-year period is much more consistent across the entire distribution.

Table 35. Reductions in total P load resulting from manure technology by time for selected sites and practices, high soil P simulations.

Practices	Technology	Reduction in Average Annual Total P Load (%)					
		JBT18		M1		JBT01	
		Year 1-10	Year 11 - 20	Year 1-10	Year 11 - 20	Year 1-10	Year 11 - 20
None	DAF	6.3	30.0	11.1	29.1	4.1	35.1
None	evaporation	7.4	31.3	11.3	29.5	6.3	39.7
No-till	DAF	10.2	30.5	13.9	24.5	4.5	29.9
No-till	evaporation	12.6	34.0	15.5	26.8	3.4	22.8
Cover Crop	DAF	2.5	24.1	6.3	22.4	0.7	23.9
Cover Crop	evaporation	3.7	24.2	6.3	23.0	3.9	35.2
Cover Crop/No-till	DAF	2.8	21.4	-0.4	13.0	-0.7	24.7
Cover Crop/No-till	evaporation	5.0	24.8	4.8	18.8	-2.0	19.2
	Median	5.7	27.4	8.7	23.7	3.7	27.3

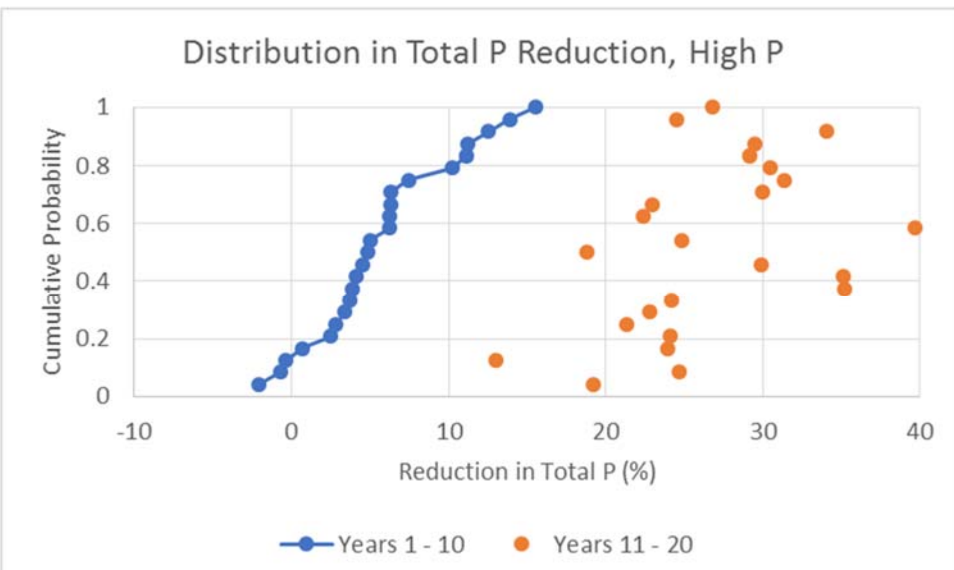

Figure 15. Cumulative distributions of average annual total P load reductions resulting from manure technologies over first ten-year and second ten-year periods. Each point plotted for "Years 11 -20" represents the same manure technology scenario as the corresponding point (i.e., same Cumulative Probability") on the "Years 1 – 10" curve for high P scenarios.

The significant total P load reductions observed in the year 11 – 20 of the 20-simulations suggests that the ability to lower P inputs from manure and manure products leads to drawdown in available soil P which ultimately lowers off-field loads through tile drainage and surface transport. To investigate the representation of this process in the APEX model, we evaluated two simulations based on the evaporation manure technology and a no-till conservation practice for the M1 and JBT18 sites. Annual time series plots of total P in the plow layer (to six inches) and total P applied in manure products are shown below in Figure 16 and

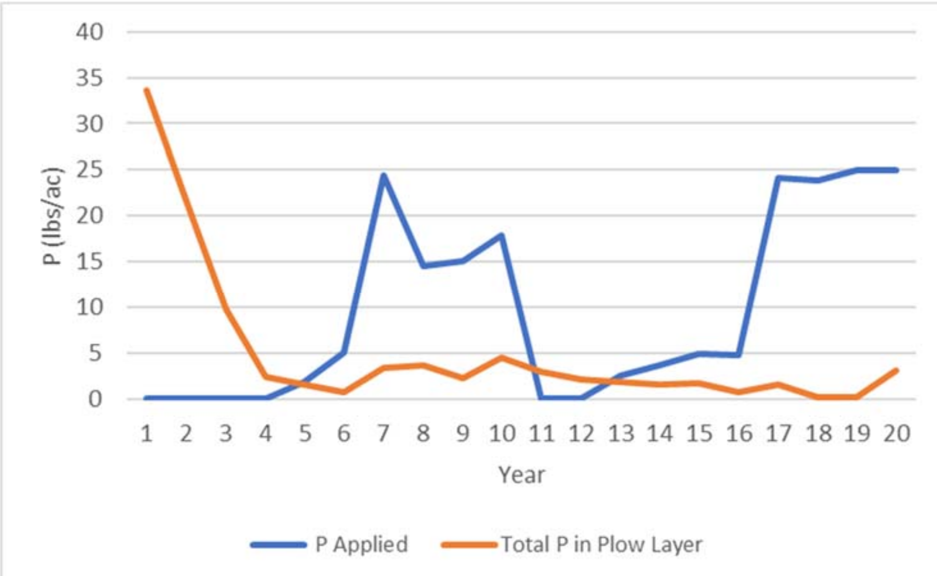

Figure 17 respectively. In both scenarios, the total P is drawn down over the first several years of the simulation, and no P fertilizer applications occur. Once the P in the plow layer is drawn down to a level that starts to negatively impact crop growth, manure product applications resume, and soil P levels stabilize. In the case of JBT18, the years of the rotation where hay is grown (years 6 – 10 and 16-20) call for higher fertilizer rates than the corn years of the rotation (years 1 – 5 and 11 – 15). The deeper root systems of corn are likely able to extract P from below the plow layer, thus higher P application rates are not needed.

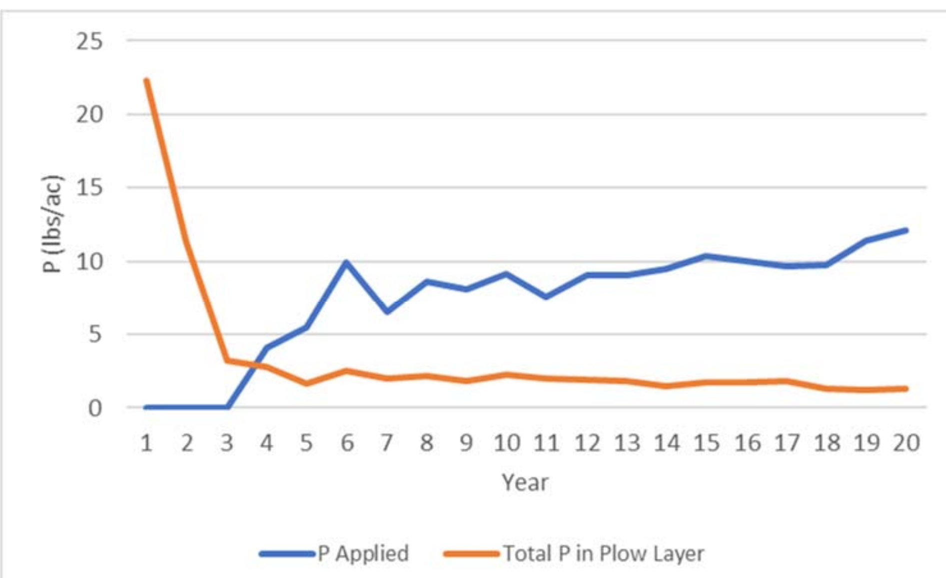

Figure 16. *P applied from manure products from evaporation technology and total P in plow layer under no-till conservation practices for site M1 with high P soils.*

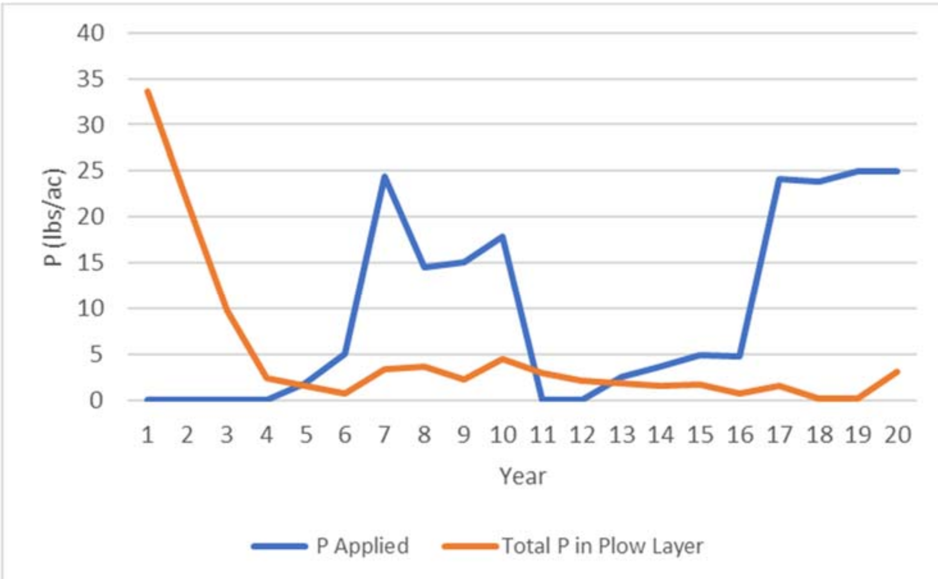

Figure 17. P applied from manure products from evaporation technology and total P in plow layer under no-till conservation practices for site JBT18 with high P soils.

The evaluation of high soil P scenarios with the adoption of manure management technology has demonstrated that one of the greatest benefits to this technology is the ability to potentially reduce P inputs from manure and allow soils with excessive phosphorus to be drawn through crop uptake and off-site transport until an equilibrium can be reached where P inputs match crop demands without having a detrimental effect on crop growth and yields. Furthermore, this analysis showed that overall, the benefits of on-field conservation practices can be implemented in coordination with manure technology while maintaining the P load reduction effectiveness of those on-field practices.

P loads for each scenario as well as bar charts showed the relative comparison of loads across scenarios for each site independently are provided in Appendix G. Note that for evaluation of trends in the different sources of P (tile, surface, and sediment), the y-axis scale varies in these charts.

3.4. Inform Existing Agency Efforts on Modeling Applications and Outcomes

Task 4 of this project called for attending and presenting at two Tile Drain Advisory Group (TDAG) meetings during the project. One of the objectives of this project was to directly address several research needs identified in the 2017 Vermont Subsurface Agricultural Tile Drainage Report (i.e., quantification of phosphorous concentrations and loads in drain flow; comparison of phosphorus concentrations and loads in drain flow with surface runoff; evaluation of factors controlling phosphorus transmission in tile drainage and; evaluation of the effectiveness of management practices to reduce phosphorus loads in tile drain flows). A Tile Drain Advisory Group meeting was not been held until late in 2019, so in lieu of presenting at a meeting early in the year, the grant workplan and completed task 1 documents were sent to Laura DiPietro on July 2, 2019 with a request for feedback from the Tile Drain Advisory Group. Subsequently, select project team members participated in a meeting with the Tile Drain Advisory Group (TDAG) on December 20th, 2019 to share the outcomes from tasks 1 and 2 and the proposed approach for task 3 of the project. The feedback provided by the TDAG resulted in a modest revision to the APEX model calibration and validation methodology and discussion, which is reflected in this Final Report.

The outcomes of this project inform agency efforts in several areas. First, the work completed in task 2 provides a calibrated and validated APEX model that can be integrated into Newtrient's phosphorus protocol to enable evaluation and comparison of practice and/or technology scenarios to reduce phosphorus in the Lake Champlain Basin. Second, the work completed in task 3 provides valuable insights on the effectiveness of best management practices and innovative manure management technologies to reduce phosphorus loading in the Lake Champlain Basin.

4. Quality Assurance Tasks Completed

The following represents a summary of the quality control tasks completed during this study.

4.1. Identification of Monitoring Sites for Modeling

The primary quality objective achieved in this task was assurance that the most representative field monitoring sites with highest quality data were selected for conducting APEX model calibration and validation. The criteria used for selecting sites and description of data associated with each site are described in Section 3.1.1.

4.2. APEX Model Calibration/Validation

The primary quality objective of this task was to develop a well-documented, robust, and scientifically defensible APEX model parameterization that performs well across Vermont agricultural sites. All calibration/validation steps and logic were fully documented within Processing Documents (PDs) and associated Quality Control Check (QCC) documentation conducted by an independent reviewer. This included reviews of all baseline model inputs established for the initial parameterization of the models for each of the 12 fields sites, checks on all model calibration inputs and output statistics for each of the four calibration steps, and reviews of all model output figures and tables to ensure accuracy. Calibration and validation efforts are fully described in Section 3.2.

4.3. Parameterization of Manure Management Scenarios/Technologies

The primary quality objective associated with this task was to develop well-documented APEX parameterizations and example scenarios that reflect the different manure management technologies and on-field conservation practices evaluated. All steps and logic involved in the development of manure management technology parameterizations and scenarios were document within Processing Documents (PDs) and associated Quality Control Check (QCC) documentation conducted by an independent reviewer. This included reviews of all APEX model input files for each scenario simulated to ensure they were accurate and as intended, evaluation of output files for each of the scenarios simulated to assess results, and checks on transcription of model outputs for the generation of tables and figures. A description of these scenarios and parameterizations is provided in Section 3.3 of this report.

5. Deliverables Completed

This section provides a discussion of the deliverables completed as part of this project.

5.1. Quality Assurance Project Plan

A secondary data quality assurance project plan (QAPP) was completed on February 21, 2019.

5.2. Quarterly Reports

Quarterly reports were prepared and submitted to the Lake Champlain Basin Program and NEIWPCC on 1/10/2019, 4/10/2019, 9/10/2019, and 1/10/2020.

5.3. Project Task Memos and Presentations

A project memo associated with the completion of Task 1 (Compilation and Evaluation of Field-Level Monitoring Efforts) was delivered to the LCBP on 5/21/2019.

A project memo associated with the completion of Task 2 (Model Calibration and Validation with Monitoring Data) was delivered to the LCBP on 12/2/2019.

A presentation to the Tile Drain Advisory Group (TDAG), reporting on the completion of Task 2, was delivered on 12/20/2019.

A follow up memo associated with revisions to the completion of Task 2 (Model Calibration and Validation with Monitoring Data) was delivered to the LCBP on 1/23/2020.

5.4. Final Report and Deliverables

The final report and deliverables included a written final report (this document).

6. Conclusions

The outcome of this project was a robust APEX modeling approach and parameterization capable of representing edge-of-field P loads (both via surface transport and tile drainage) for investigating P load reductions resulting from innovative manure management technologies and on-field conservation practices. This work addressed the need for quantification of P loads from tile drain flow under various conditions, as well as provides a basis for comparing P load from tile flow and surface runoff, and for evaluating factors influencing P movement in tile drainage. The research effort also provided an initial quantitative assessment of the potential value of manure management technologies in reducing P loads from agricultural fields, which has the potential to play a role in improving water quality outcomes at the farm and basin scale.

The calibration of a robust APEX model parameterization focused on an evaluation of five Vermont fields with edge-of-field surface monitoring, six Vermont fields with tile drain monitoring, and one New York site with both tile and edge-of-field monitoring. The resulting calibration/validation effort identified a global parameterization of the model that minimized model prediction bias and minimized the magnitude in model error in annual total P load predictions over seven calibration sites and were found to result in comparable model performance at five independent validation sites. The steps in the calibration process that focused on a global parameterization, i.e., a set of parameters that are applied to all sites, had the greatest relevance for implementation of APEX-based modeling to quantify P loads across broad areas of Vermont's agricultural landscape at unmonitored sites. The results of the global parameterization calibration using representative soils properties demonstrated that on average, APEX simulations of average annual total P load would be less than 37% above or below measured values, with two thirds of sites deviating by less than 25% above or below measured values. Furthermore, the model simulations had no systematic bias (over versus under predicting monitoring data), showing a positive/negative bias of less than 1% across all twelve sites. The associated Monte Carlo analysis of soils parameter demonstrated that uncertainty in best available soils datasets can account for the observed bias in APEX simulation results, and that selection of "best" soils parameters within the range of uncertainty will often lead to improvements in model performance. This finding suggests that APEX model simulations based on site-specific soil properties will likely have reduced bias in average annual P load predictions.

Using the APEX models for five sites (four tile drained and one undrained) developed using the global parameterization and site-specific soils, a suite of scenarios was simulated to assess the implementation of manure management technologies and a selection of conservation practices. These APEX simulations were designed to demonstrate the potential reduction of P loads that could be obtained through combinations of two manure technologies (DAF and evaporation) and four conservation practices (no-till, cover cropping, manure injection, and no-till plus cover cropping). The results of 114 scenario simulations showed that both P loads from surface transport and tile drain transport can be reduced with these practices and technologies. When P levels in the soil are close to optimal and manure-based nutrient inputs are not excessive, the benefits realized by the implementation of manure management technology ranged from a 6% increase to as much as a 13% decrease in total P loses, with a median decrease of 6%. For scenarios where soil P was high and manure applications were higher than crop demand, the predicted benefits of manure technologies increased. Under these situations, the median total P load reduction was 15%, and as high as 30% in some scenarios. It was also found that this benefit was greater following a 10-year period after the initial adoption of manure technology, as a result of drawing down excessive P in the soil over time. In evaluating the second 10-year period after adoption of manure technologies, the APEX simulations suggested that median reductions in P loads of between 24% and 27% could be achieved, with some scenarios resulting in a 40% reduction in P loses. The modeling of technologies and practices focused only on phosphorus metrics due to its importance to water quality in the Lake Champlain Basin. However, the overall impact of technologies on other nutrients, such as nitrogen, was not part of this study but will likely provide additional incentive in support of manure technology adoption.

This project addressed several research needs identified in the 2017 Vermont Subsurface Agricultural Tile Drainage Report, including quantification of phosphorous concentrations and loads in drain flow; comparison of phosphorus concentrations and loads in drain flow with surface runoff; evaluation of factors controlling phosphorus transmission in tile drainage and; evaluation of the effectiveness of management practices to reduce phosphorus loads in tile drain flows. Central to addressing all of these research needs described above was development of a modeling approach capable of simulating P transport due to runoff, erosion, and subsurface flow through tile drainage networks, as well as assessing the P load reduction benefits of manure management technologies and on-field conservation practices. The calibration and validation of the APEX model across twelve sites in the Lake Champlain Basin represents an important milestone in the development of a systematic and unbiased approach to quantifying P load across farmland throughout the basin. With a tool that has been shown to predict both surface P loads and tile drain P loads with reasonable accuracy across crop rotations and practices found within the Lake Champlain Basin, we can now focus more energy into integration of this modeling approach within a broader phosphorus protocol aimed at incentivizing farmers to adopt technologies and practices that lead to a water quality benefit. A basin-wide adoption of such an approach to quantifying the benefits of manure technologies and conservation practices, coupled with the opportunity for incentives, should ultimately lead us more directly towards a future where goals of the Lake Champlain P TMDL have been met.

7. References

American Society of Agricultural Engineers (ASAE). 2003. Manure Production and Characteristics. ASAE D384.1 FEB03. St. Joseph, MI. 4 pp.

Augustin, C. and Rahman, S. 2010. Composting Animal Manures: A guide to the process and management of animal manure compost. NDSU Extension Service, North Dakota State University, Fargo, North Dakota.

Bosworth, S., Darby, H. 2015. Improving the Viability of Dairy Farms through Advanced Forage Selection and Management. UVM Dairy Center for Excellence Project. 5 pp.

Braun, D., Meals, D., Moore, J., and Macrellis, A. 2016. Agricultural Practice Monitoring and Evaluation. Year 4 Report. Prepared for Lake Champlain Basin Program, Stone Environmental, Inc.

Braun, D. and Meals, D. 2019. Agricultural Practice Monitoring and Evaluation. Prepared for Lake Champlain Basin Program, Stone Environmental, Inc.

Braun, D., Meals, D., and Smeltzer, E. 2019. Assessment of Phosphorus Loads in Tile Drainage in the Jewett Brook Watershed of St. Albans Bay, Lake Champlain. Prepared for Lake Champlain Basin Program, Stone Environmental, Inc.

Cornell University. 2017. New York and Vermont Corn Silage Hybrid Trials – 2017. NYS College of Agriculture and Life Sciences, Cornell University, Ithaca, NY. 32 pp.

Cornell University. 2018. New York and Vermont Corn Silage Hybrid Evaluation Program, November 29, 2018. NYS College of Agriculture and Life Sciences, Cornell University, Ithaca, NY. 38 pp.

Laura Klaiber. 2019. Nutrient Management Researcher, Minter Institute, Chazy, NY. NRCS (Natural Resources Conservation Service). 1986. Urban Hydrology for Small Watersheds, Technical Release 55. US Department of Agriculture. 164 pp.

Steglich, E.M., and J.R. Williams. 2008. Agricultural Policy/Environmental eXtender Model: User's manual version 0604 DOS and WINAPEX interface. BREC Report # 2008-16. Temple, TX: Texas AgriLIFE Research, Texas A&M University, Blackland Research and Extension Center.

Steglich, E.M., J. Jeong, and J.R. Williams. 2016. Agricultural Policy/Environmental eXtender Model: User's manual version 1501. Natural Resources Conservation Service, Blackland Research and Extension Center. Temple, TX. 241 pp.

Stone Environmental. 2015. Development of a Web-Based APEX Tool, VT STAR, for Optimizing Best Management Practices and Conservation Planning on Vermont Farms: Final Report. Prepared for the Vermont Natural Resources Conservation Service and Vermont Agency of Food and Markets by Stone Environmental, Inc., Montpelier, VT. Available at: http://www.stone-env.com/assets/resources/VT-STAR-Tool-Final-Report-13Oct2015.pdf

University of Vermont Extension. 2018. Nutrient Recommendations for Field Crops in Vermont.

US EPA Region 1 (United States Environmental Protection Agency). 2016. Phosphorus TMDLs for Vermont Segments of Lake Champlain; June 17, 2016. Boston, MA.

USDA (United States Department of Agriculture). 2019. Crop Production 2018 Summary. USDA-NASS. ISSN: 1057-7823. 132 pp.

Vadas, P. A. and M. J. White. 2010. Validating soil phosphorus routines in the SWAT model. Trans. ASABE 53(5):1469-1476. VT ANR (Vermont Agency of Natural Resources). 2014. Vermont Water Quality Standards: Environmental Protection Rule Chapter 29(a). Vermont Agency of Natural Resources, Department of Environmental Conservations, Watershed Management Division, Montpelier, VT.

Winchell, M. F., D. Meals, D. Braun, S. Folle, K. Budreski, C. DeLeo, J. Moore. 2011. Identification of Critical Source Areas of Phosphorus Within the Vermont Sector of the Missisquoi Bay Basin. Technical Report # 63B. 266 pp.

8. Appendices

Appendix A: Time Series Plots of Annual Flow and Total P Based on Global Parameterization Simulations, Representative Soil Parameters

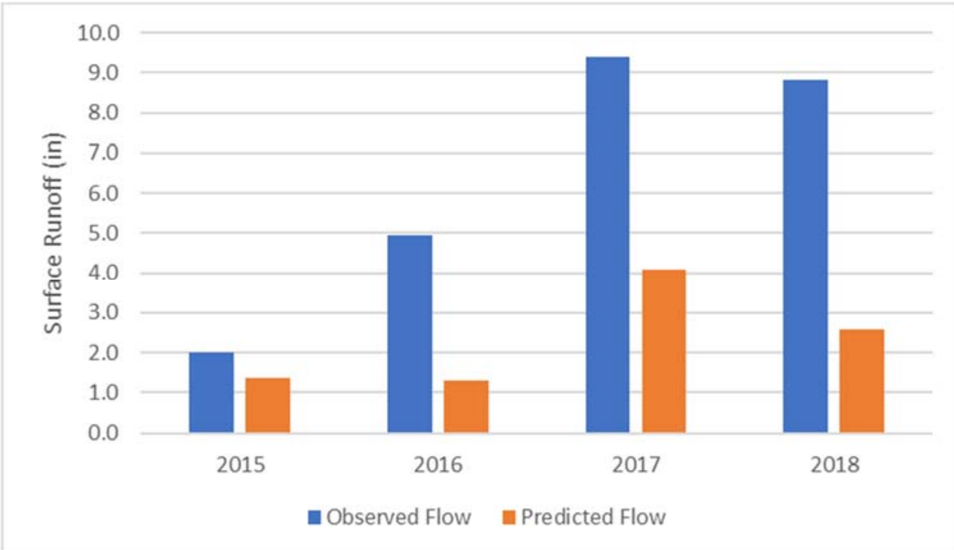

Figure 18. Observed versus model-predicted annual surface runoff (flow) at CHA1.

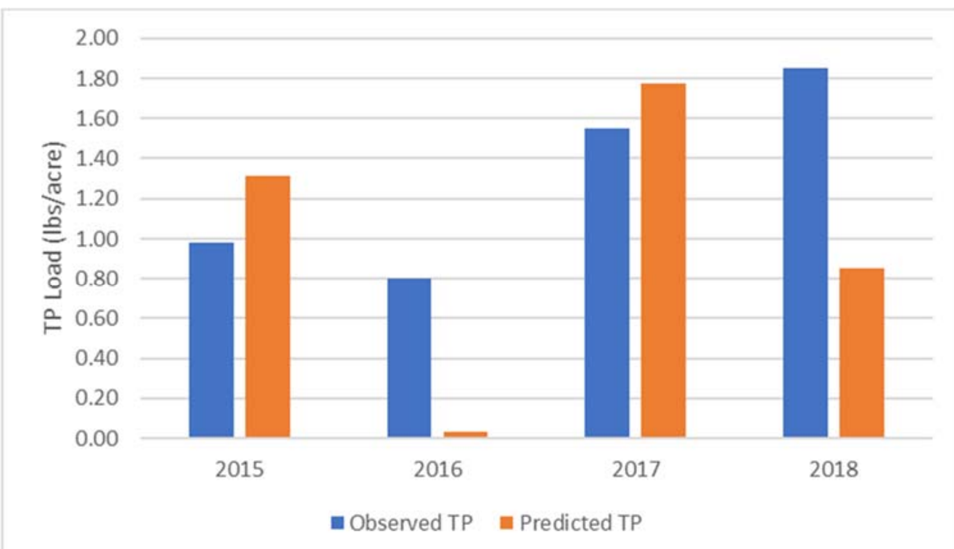

Figure 19. Observed versus model-predicted annual total P at CHA1.

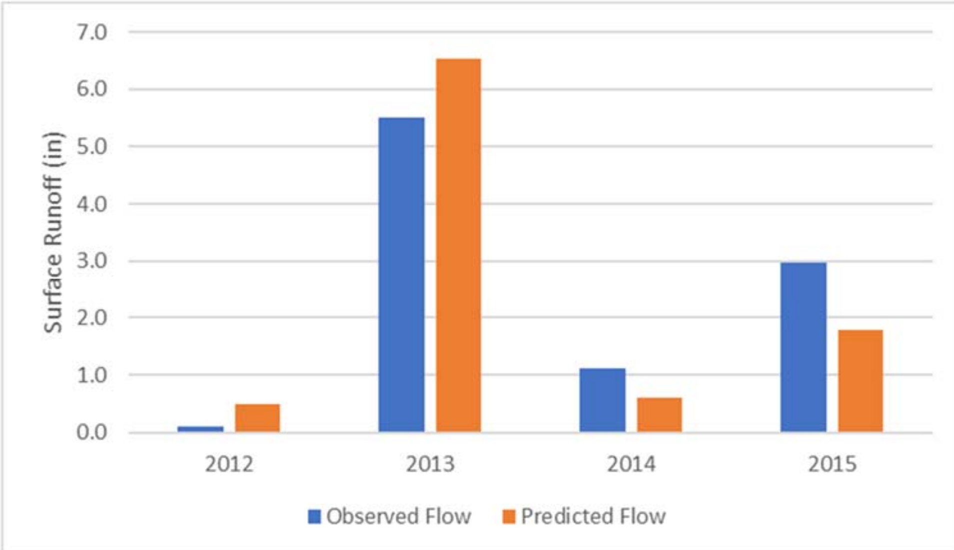

Figure 20. Observed versus model-predicted annual surface runoff (flow) at FER1.

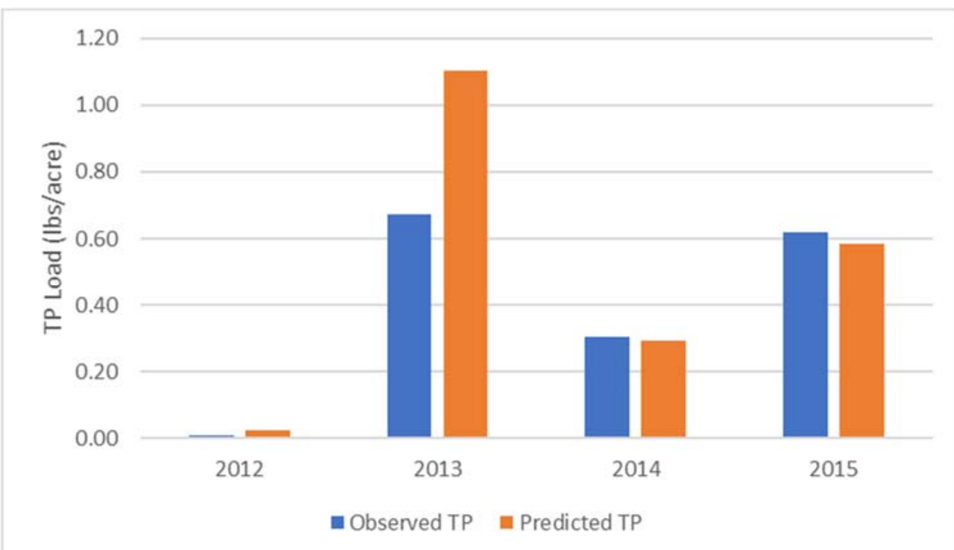

Figure 21. Observed versus model-predicted annual total P at FER1.

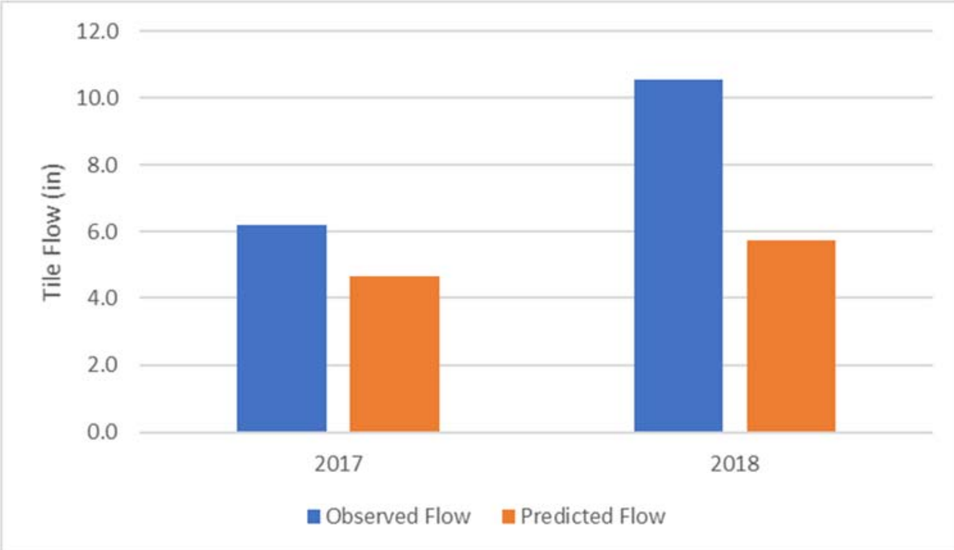

Figure 22. Observed versus model-predicted annual tile flow at JBT01.

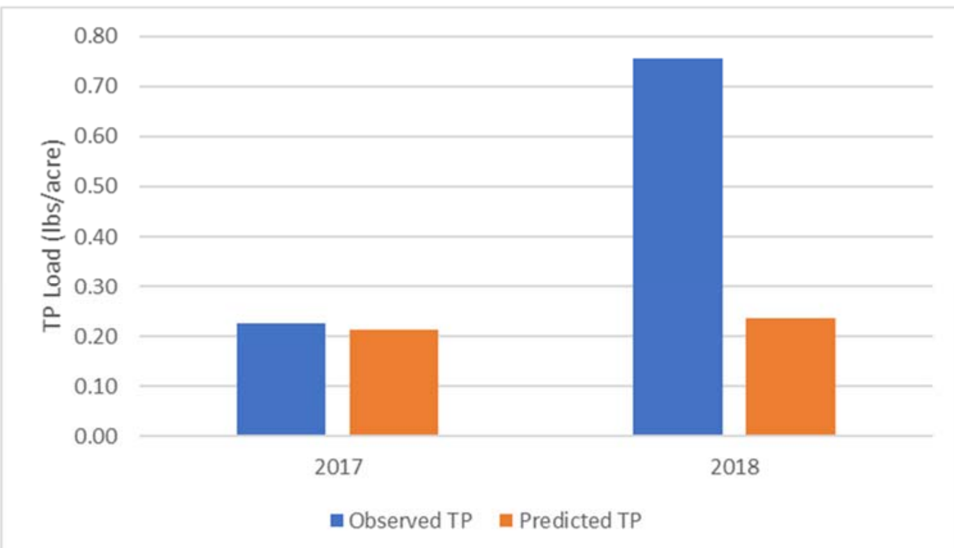

Figure 23. Observed versus model-predicted annual total P at JBT01.

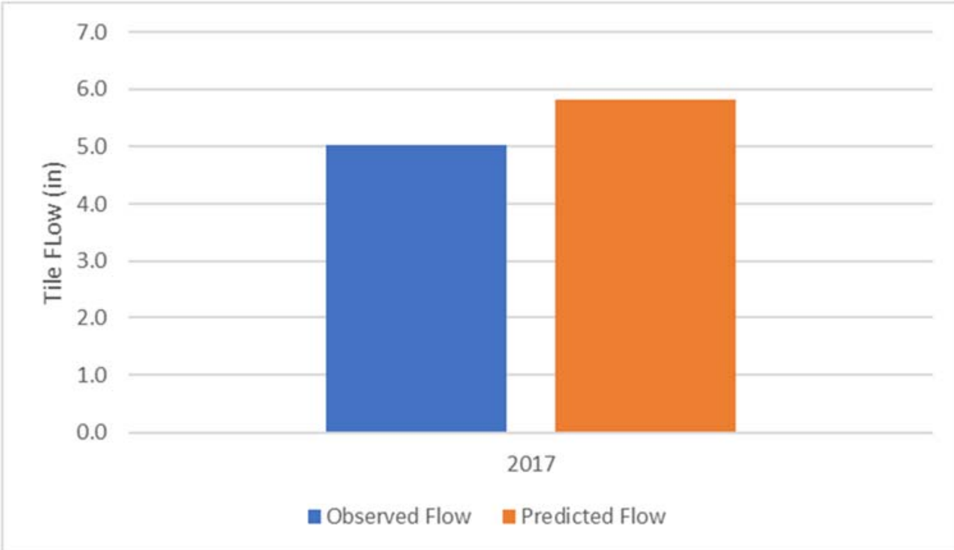

Figure 24. Observed versus model-predicted annual tile flow at JBT04.

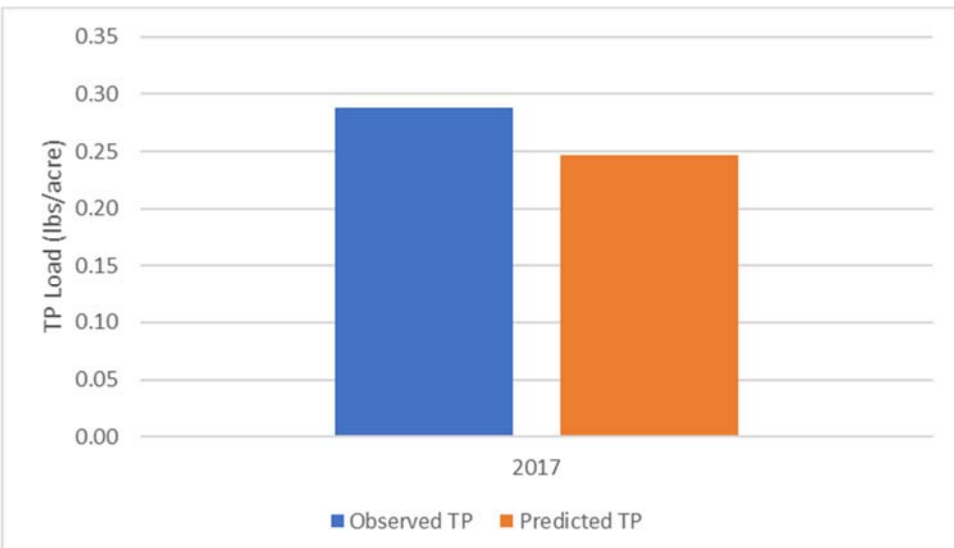

Figure 25. Observed versus model-predicted annual total P at JBT04.

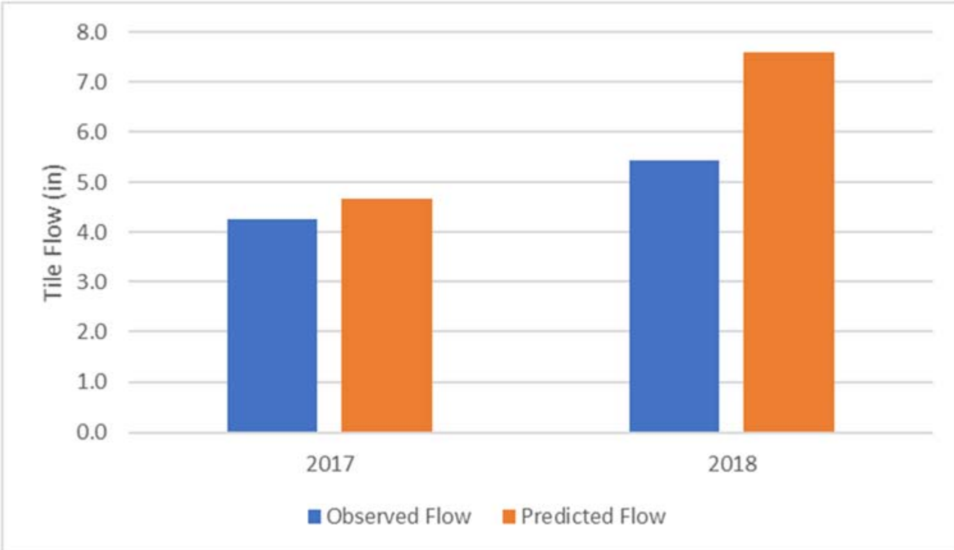

Figure 26. Observed versus model-predicted annual t tile flow at JBT05.

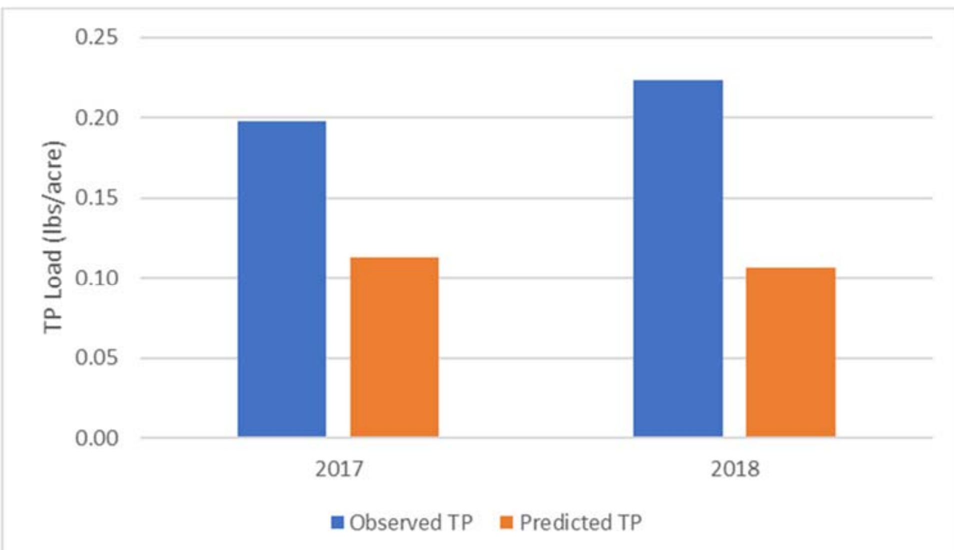

Figure 27. Observed versus model-predicted annual total P at JBT05.

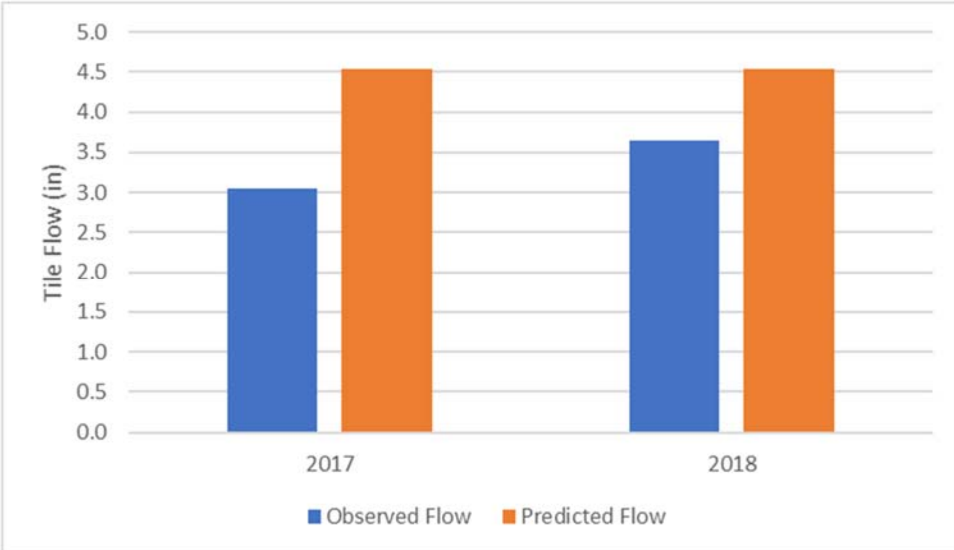

Figure 28. Observed versus model-predicted annual tile flow at JBT07.

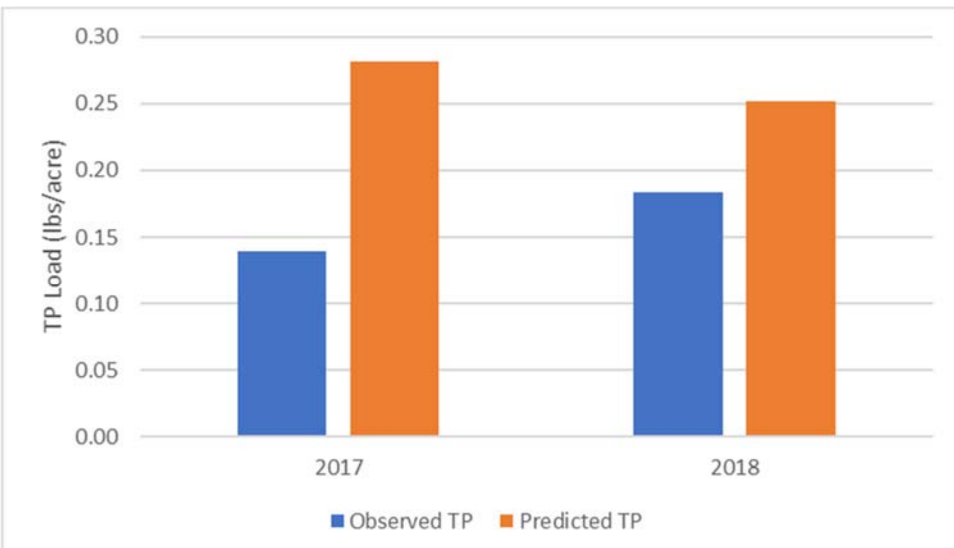

Figure 29. Observed versus model-predicted annual total P at JBT07.

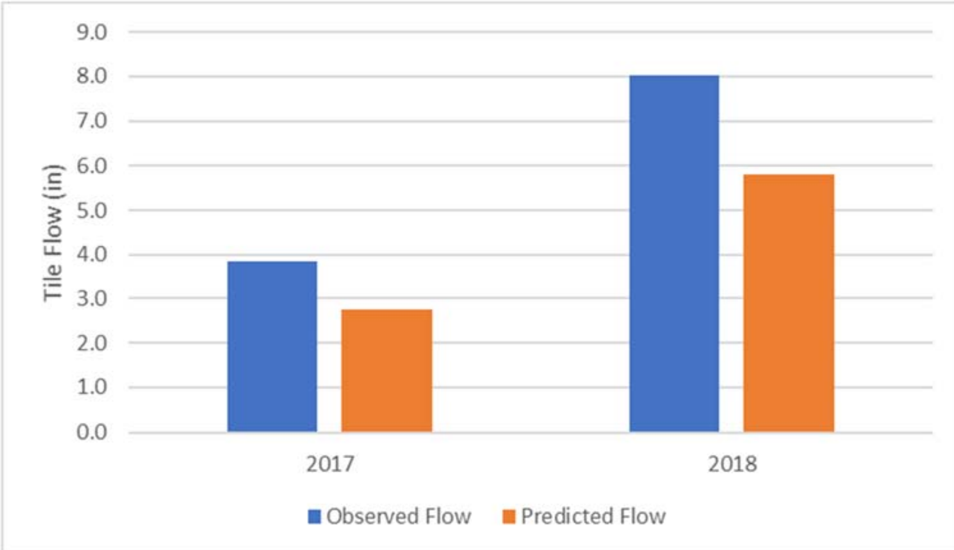

Figure 30. Observed versus model-predicted annual tile flow at JBT11.

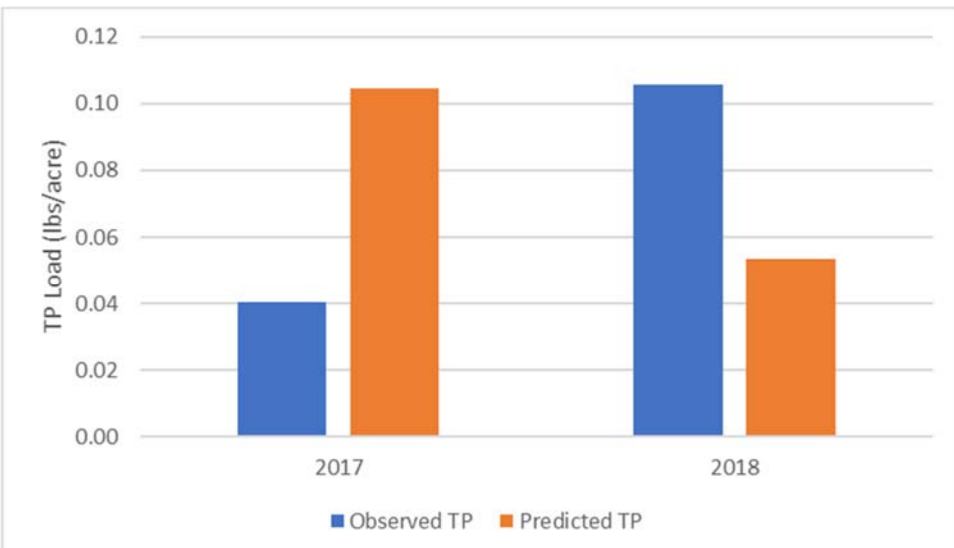

Figure 31. Observed versus model-predicted annual total P at JBT11.

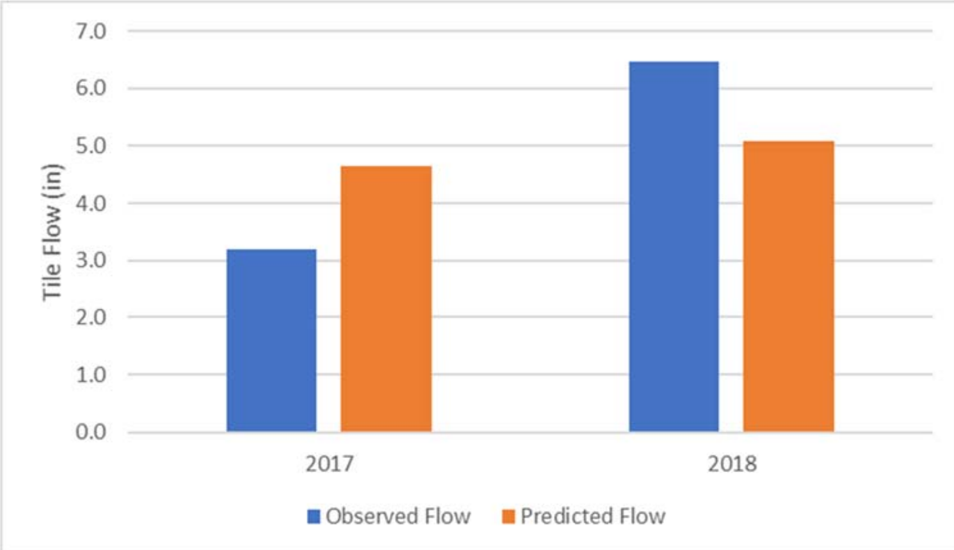

Figure 32. Observed versus model-predicted annual tile flow at JBT18.

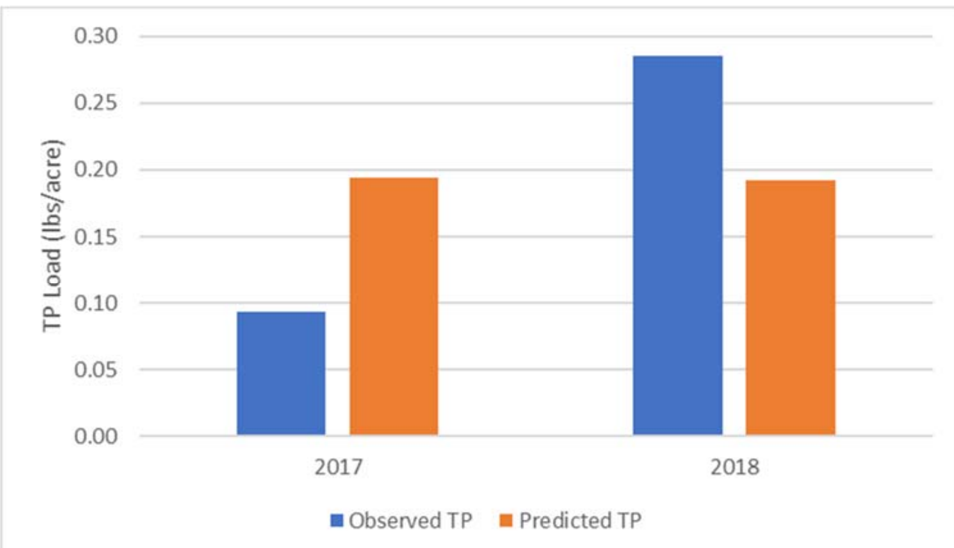

Figure 33. Observed versus model-predicted annual total P at JBT18.

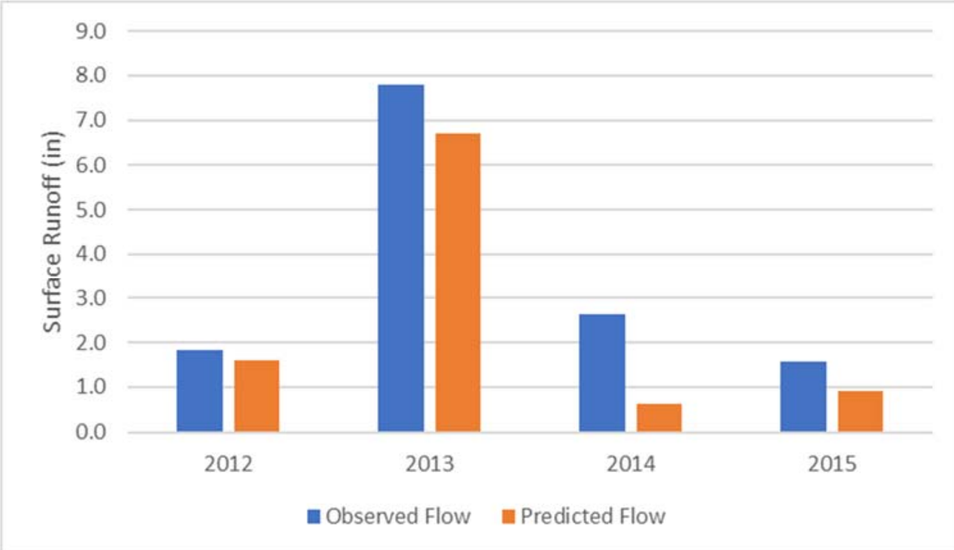

Figure 34. Observed versus model-predicted annual surface runoff (flow) at PAW1.

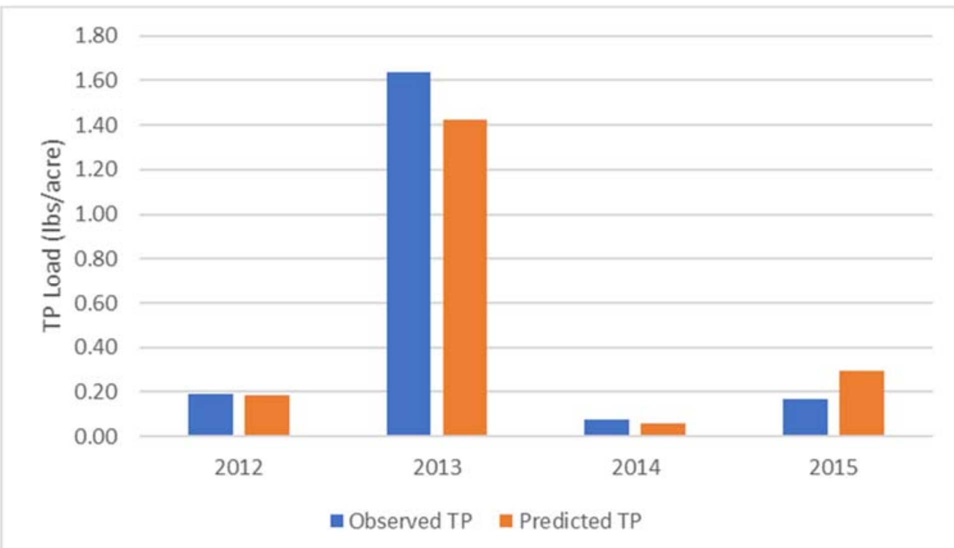

Figure 35. Observed versus model-predicted annual total P at PAW1.

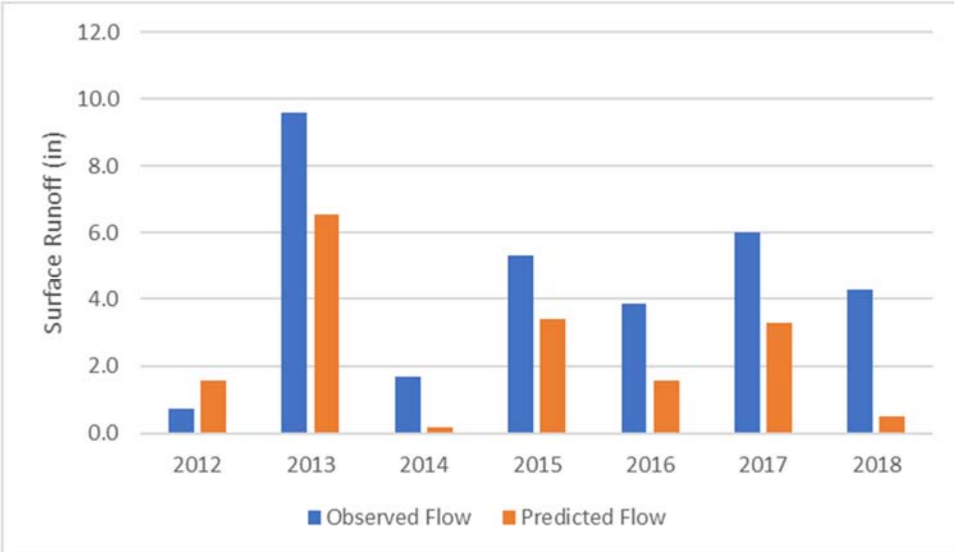

Figure 36. Observed versus model-predicted annual surface runoff (flow) at SHE1.

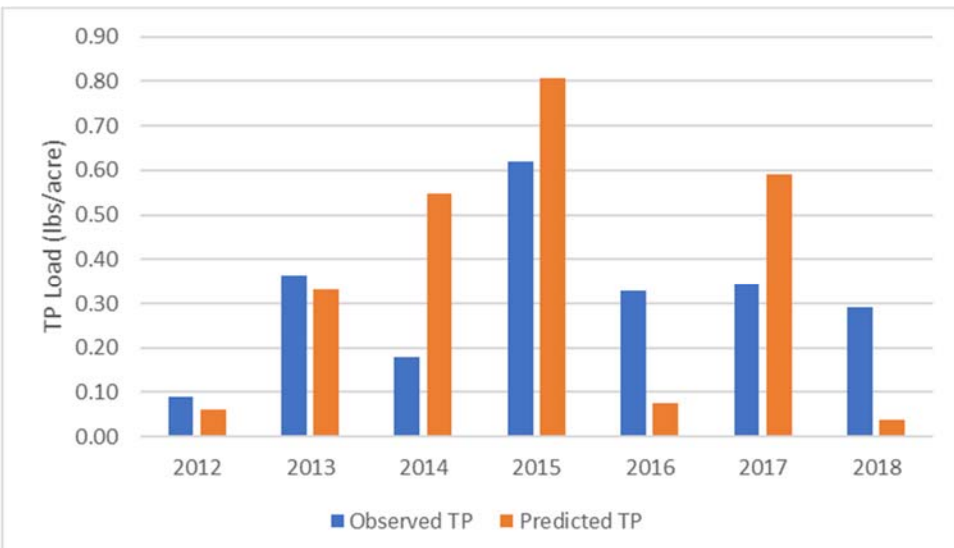

Figure 37. Observed versus model-predicted annual total P at SHE1.

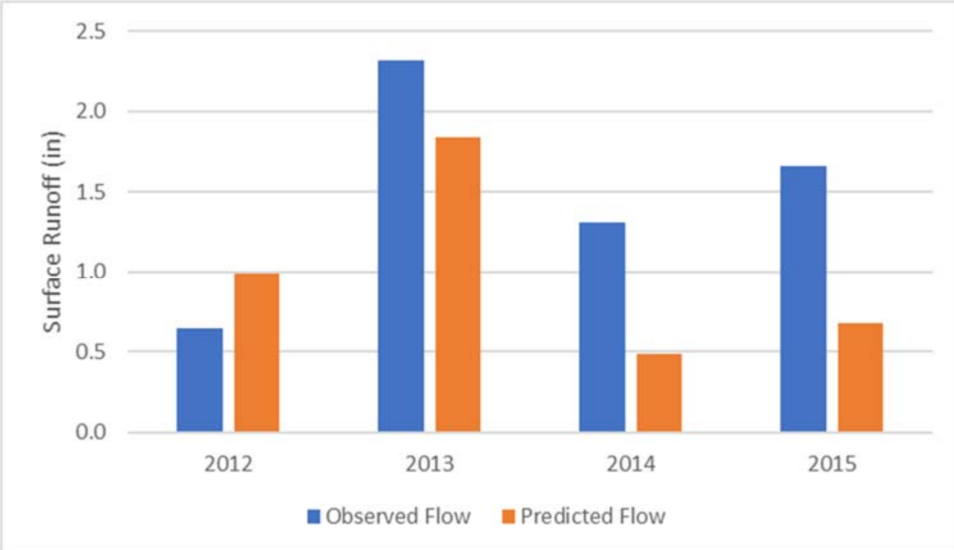

Figure 38. Observed versus model-predicted annual surface runoff (flow) at SHO1.

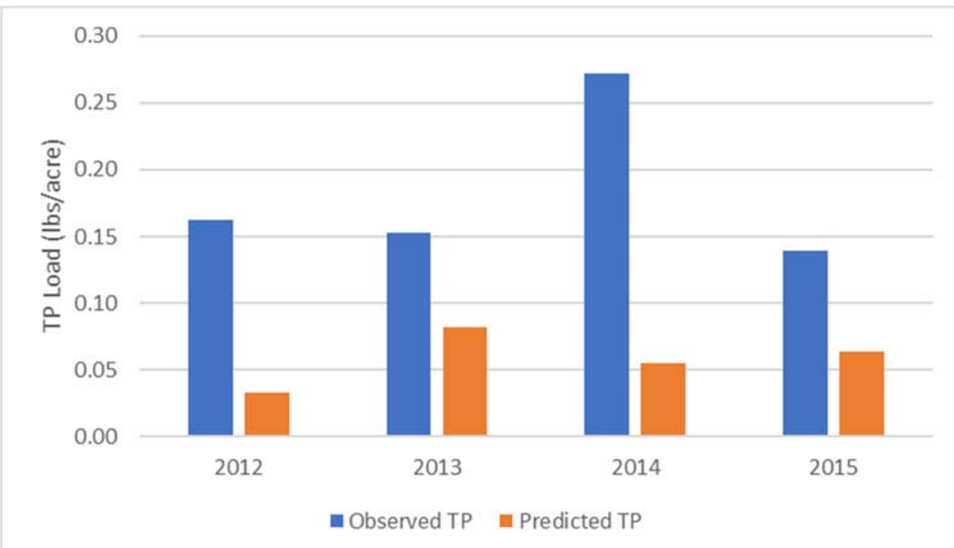

Figure 39. Observed versus model-predicted annual total P at SHO1.

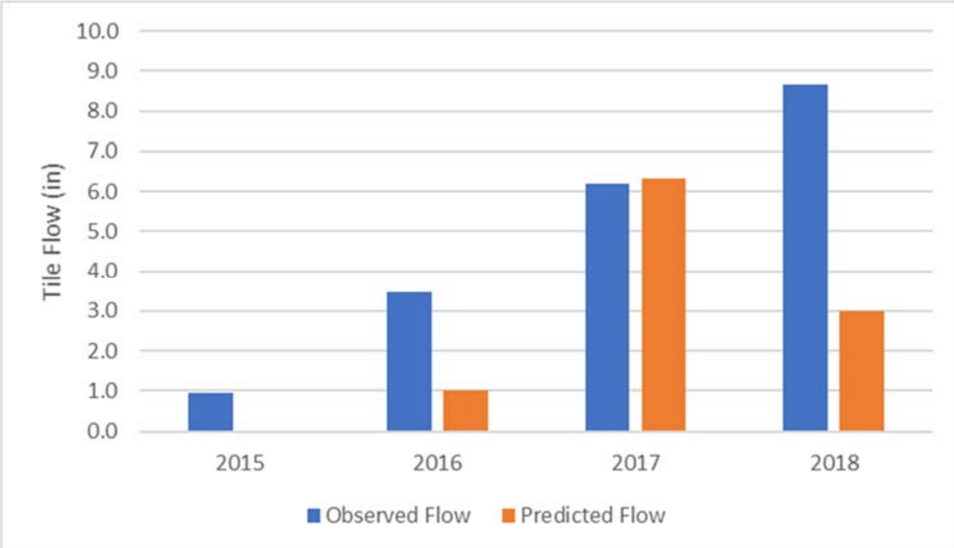

Figure 40. Observed versus model-predicted annual tile flow at M1.

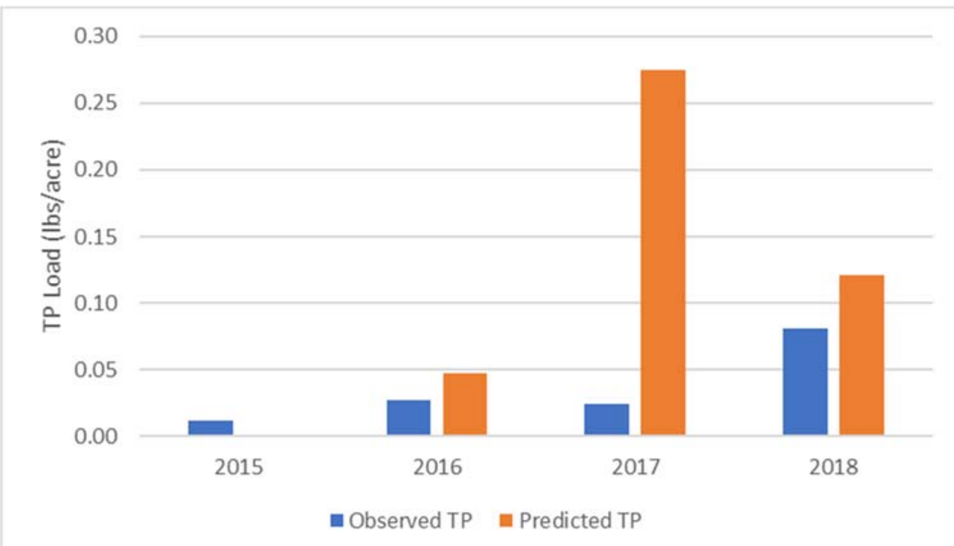

Figure 41. Observed versus model-predicted annual total P in tile flow at M1.

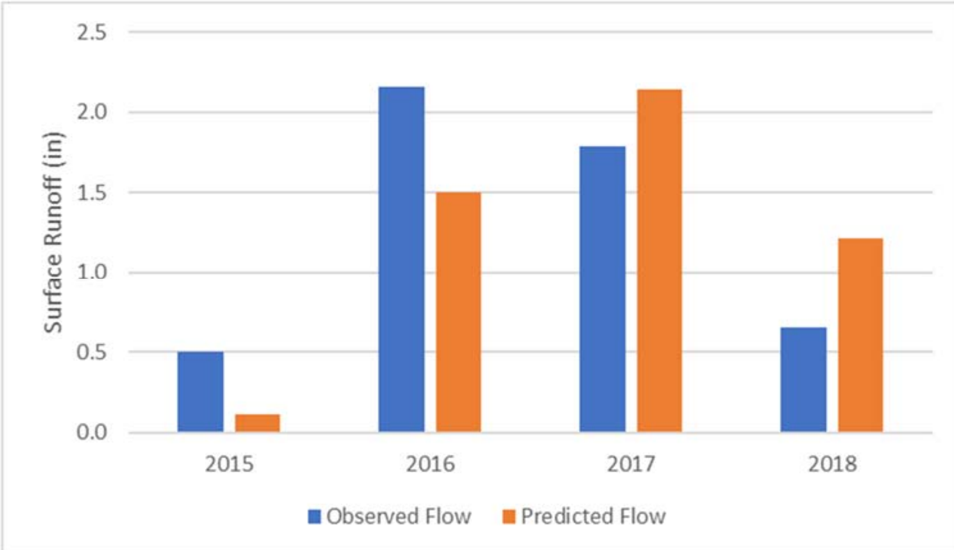

Figure 42. Observed versus model-predicted annual surface runoff (flow) at M1.

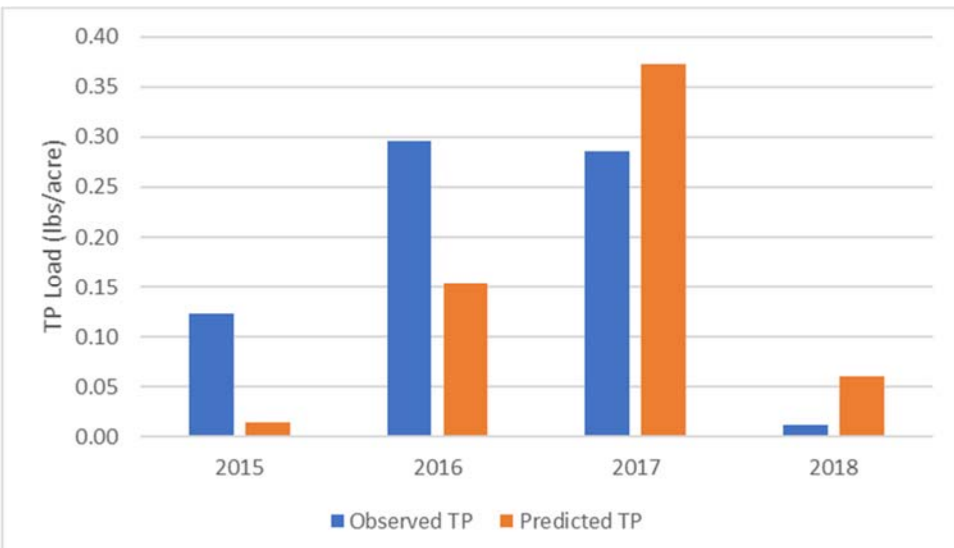

Figure 43. Observed versus model-predicted annual total P in surface runoff at M1.

Appendix B: Time Series Plots of Annual Flow and Total P Based on Global Parameterization Simulations, Best Soils Parameters

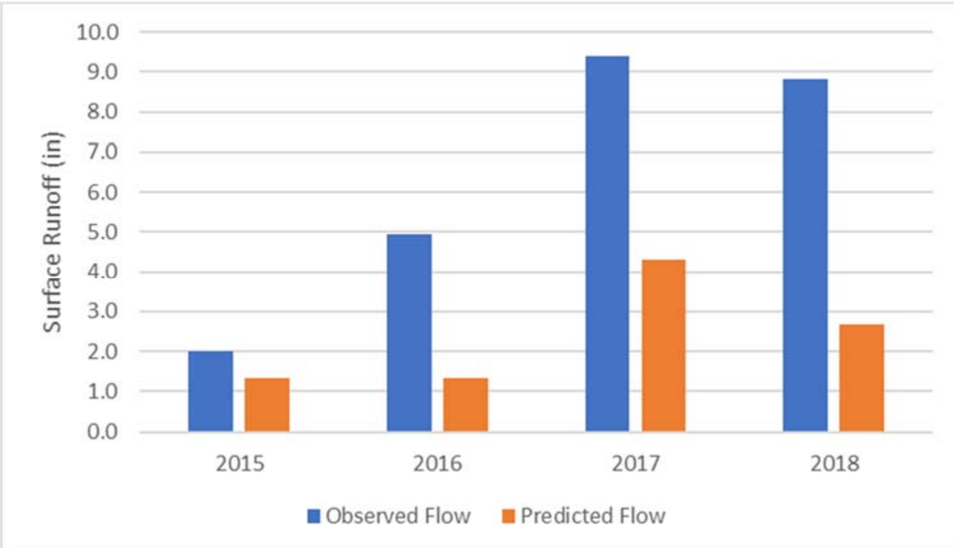

Figure 44. Observed versus model-predicted annual surface runoff (flow) at CHA1.

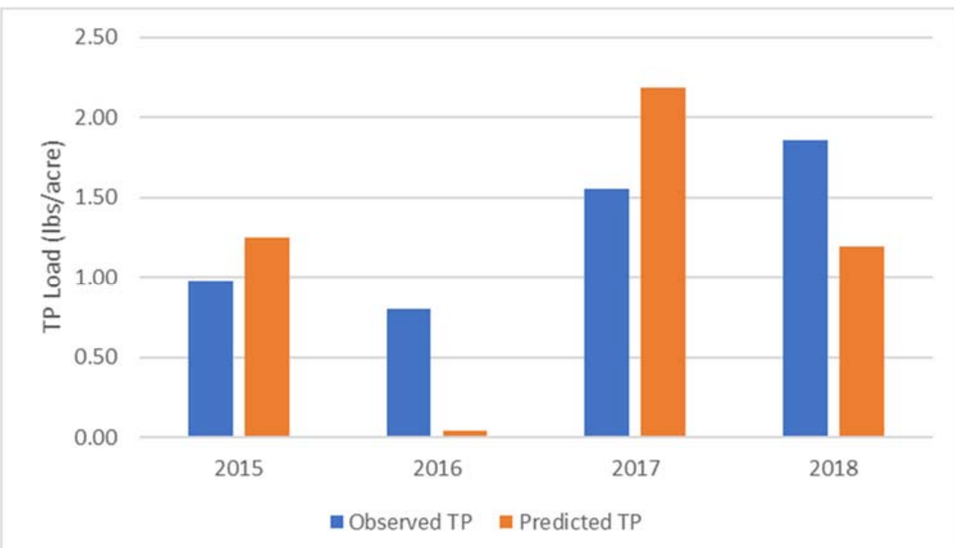

Figure 45 Observed versus model-predicted annual total P at CHA1.

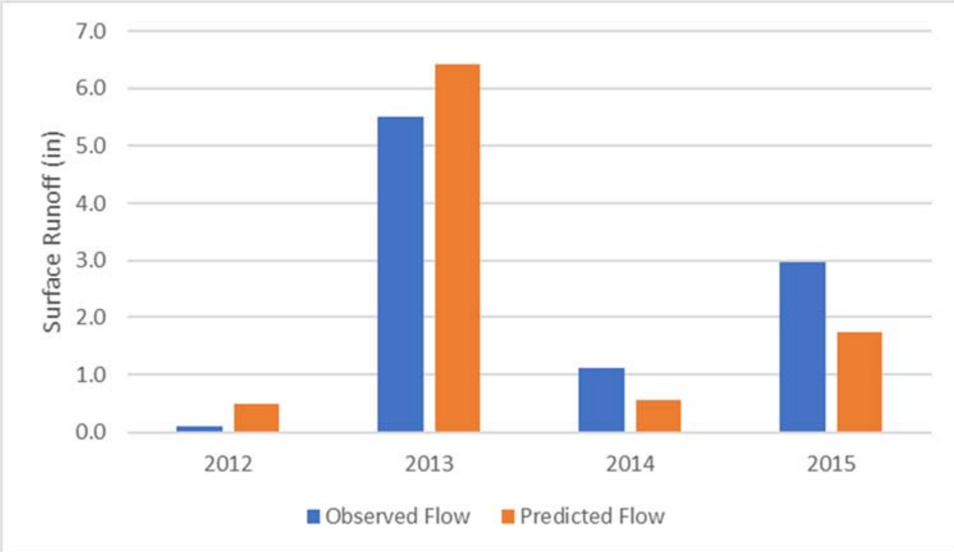

Figure 46. Observed versus model-predicted annual surface runoff (flow) at FER1.

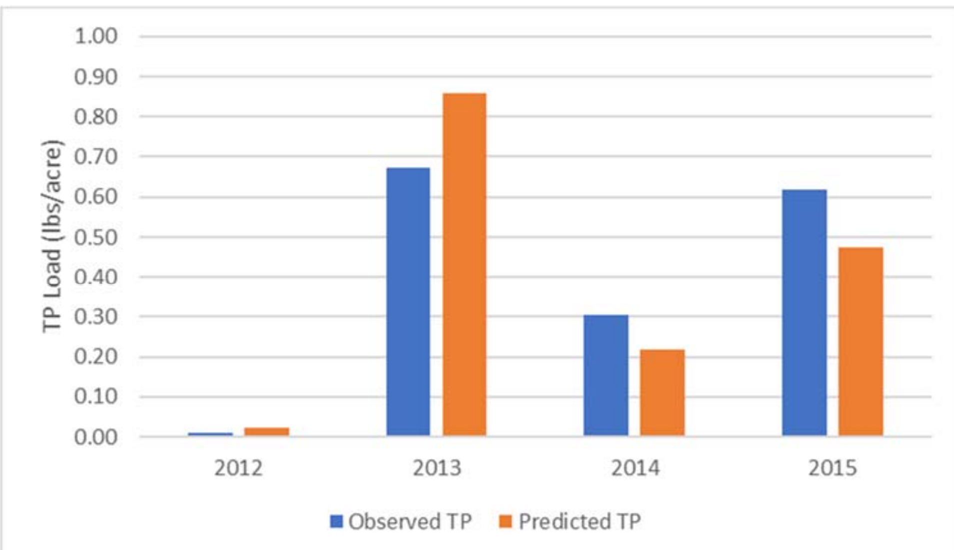

Figure 47. Observed versus model-predicted annual total P at FER1.

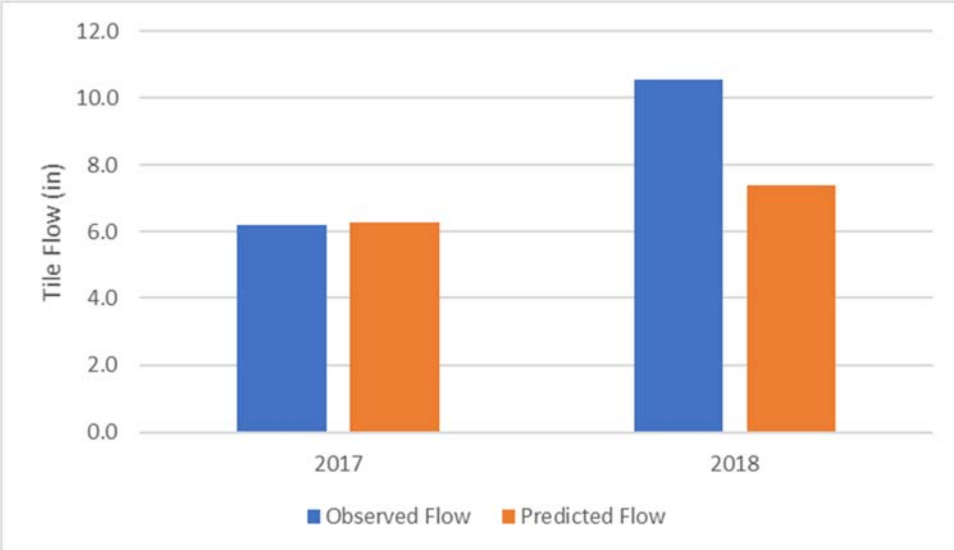

Figure 48. Observed versus model-predicted annual tile flow at JBT01.

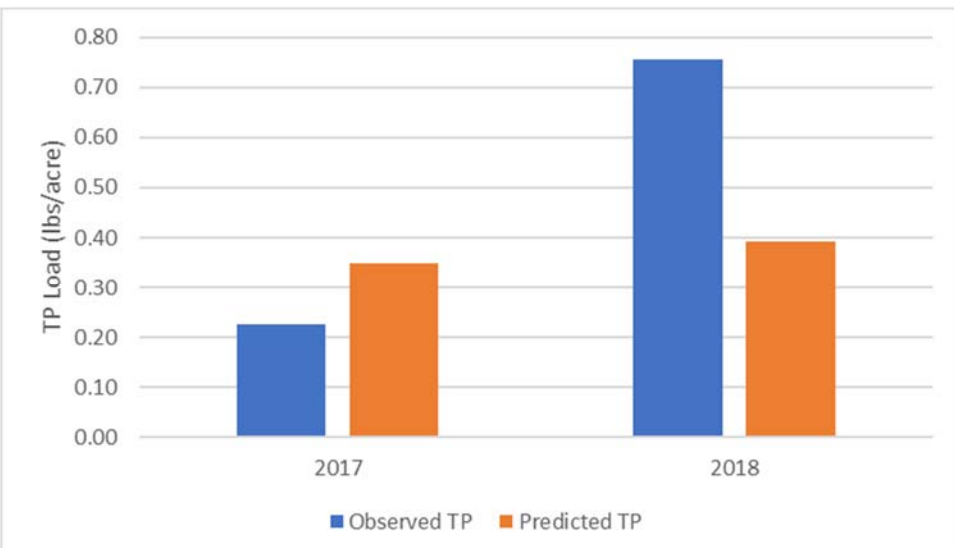

Figure 49. Observed versus model-predicted annual total P at JBT01.

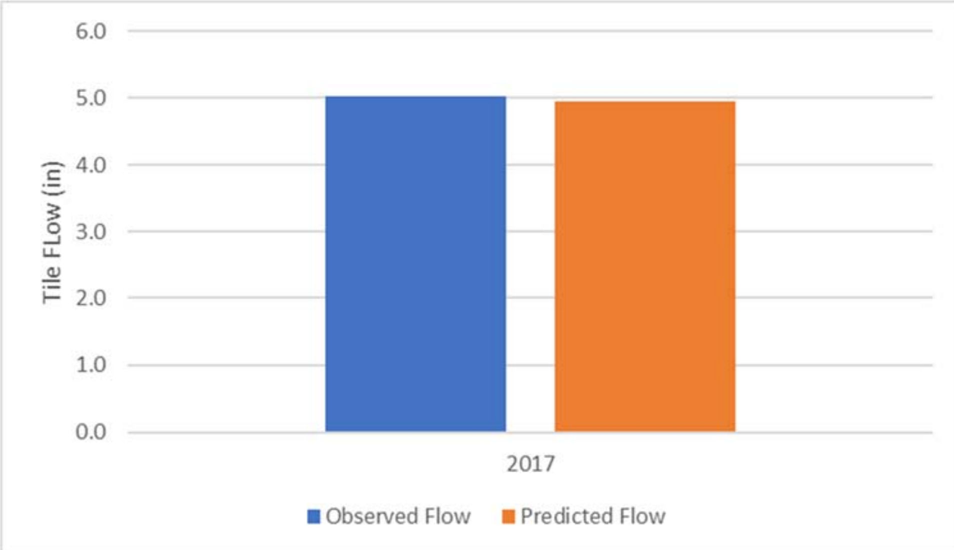

Figure 50. Observed versus model-predicted annual tile flow at JBT04.

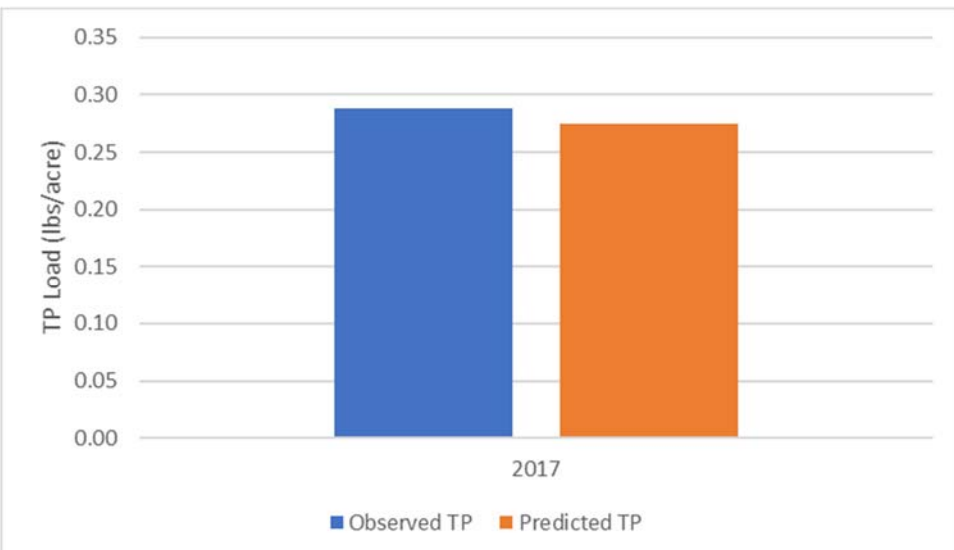

Figure 51. Observed versus model-predicted annual total P at JBT04.

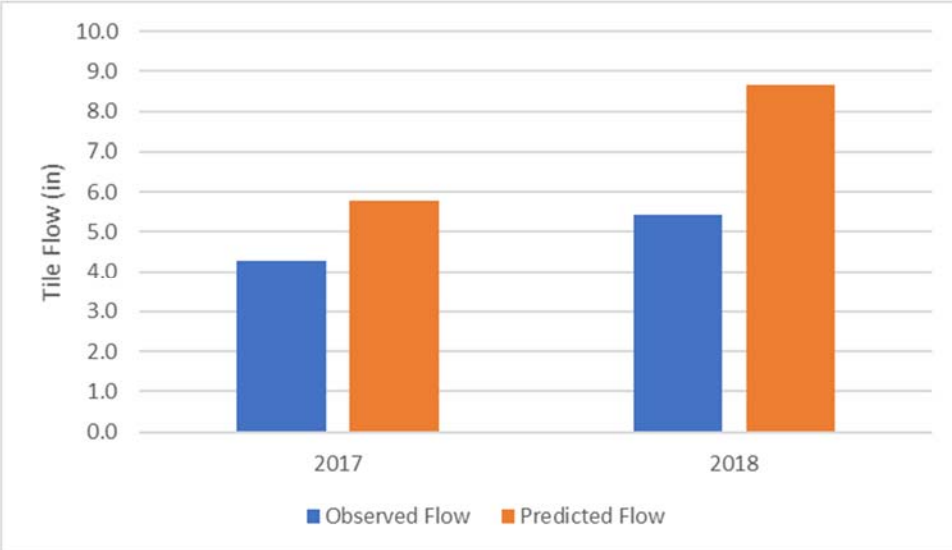

Figure 52. Observed versus model-predicted annual tile flow at JBT05.

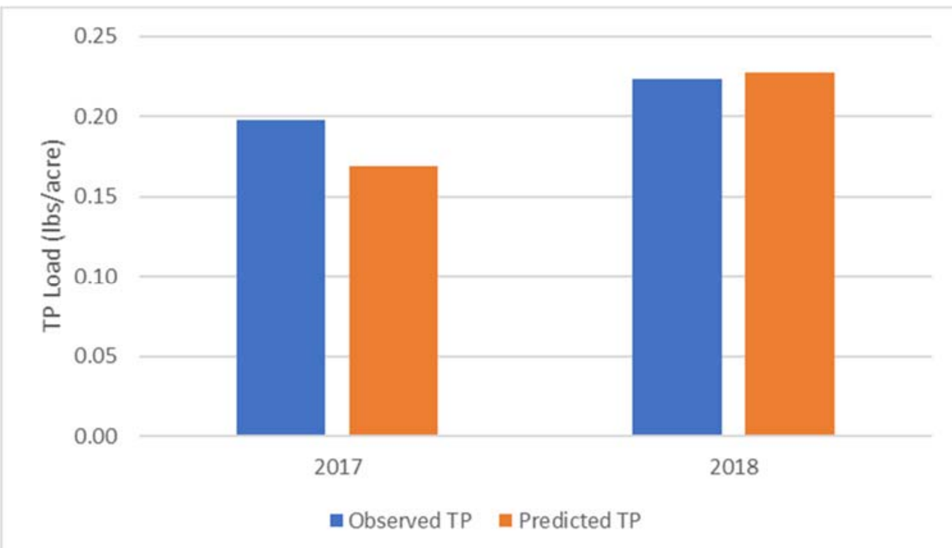

Figure 53. Observed versus model-predicted annual total P at JBT05.

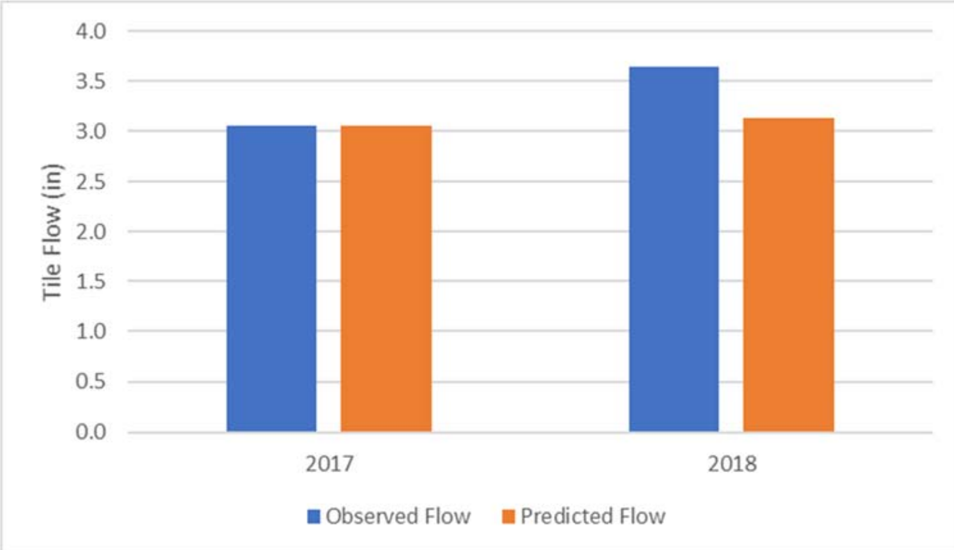

Figure 54. Observed versus model-predicted annual tile flow at JBT07.

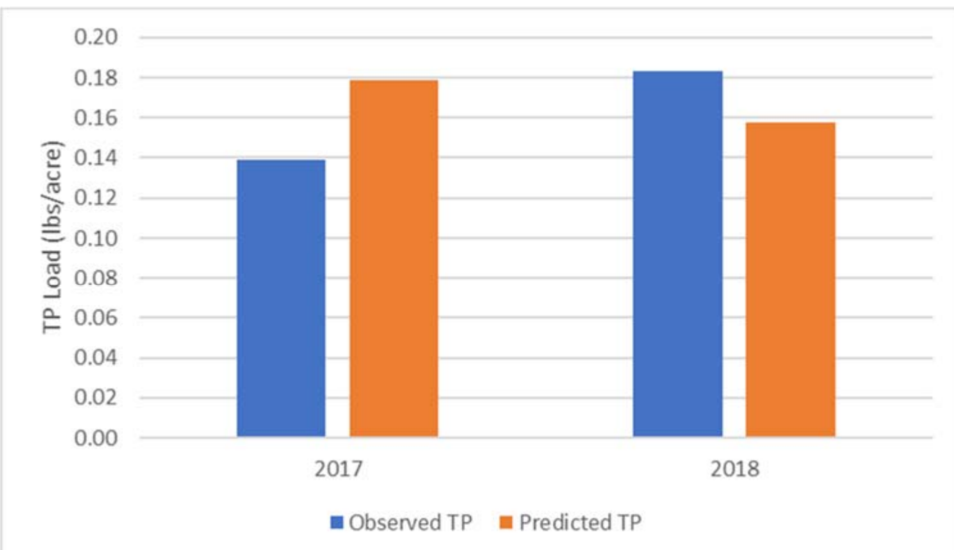

Figure 55. Observed versus model-predicted annual total P at JBT07.

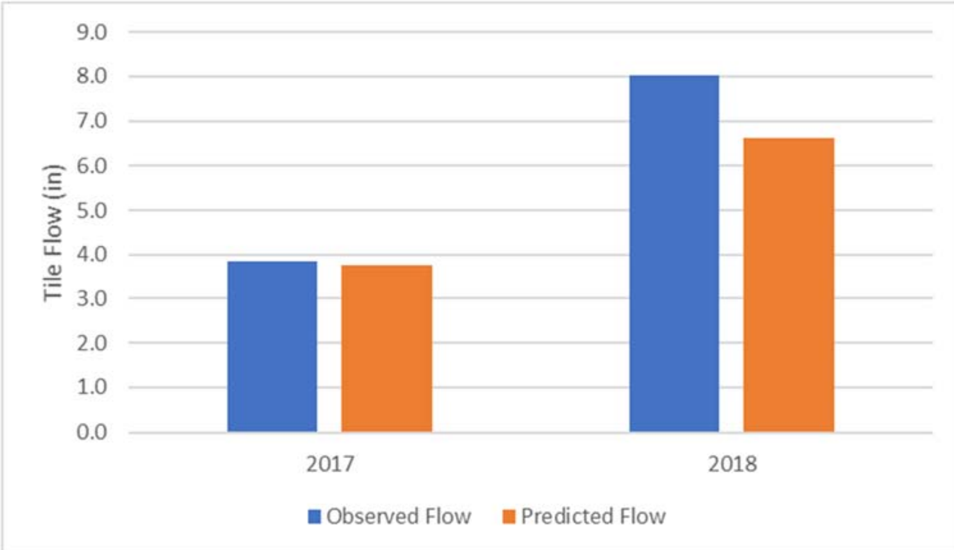

Figure 56. Observed versus model-predicted annual tile flow at JBT11.

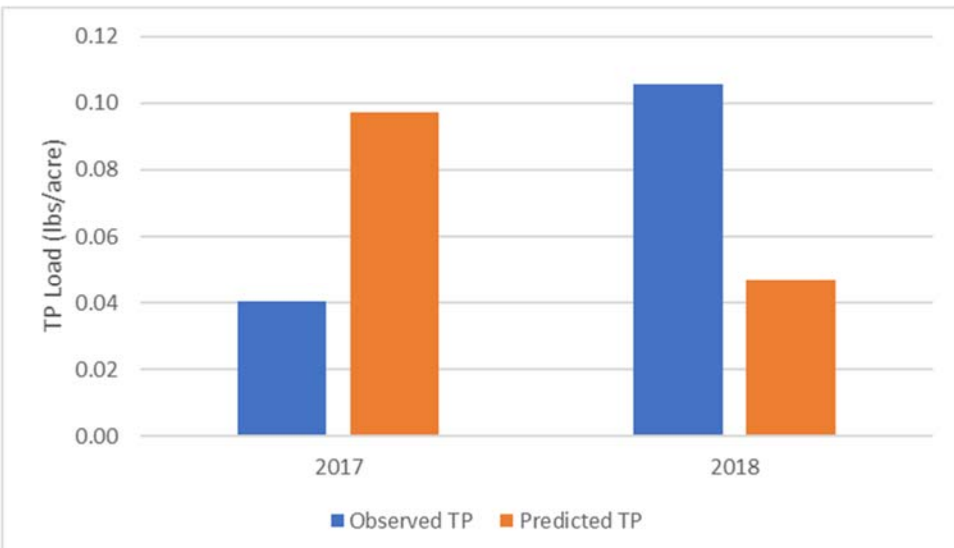

Figure 57. Observed versus model-predicted annual total P at JBT11.

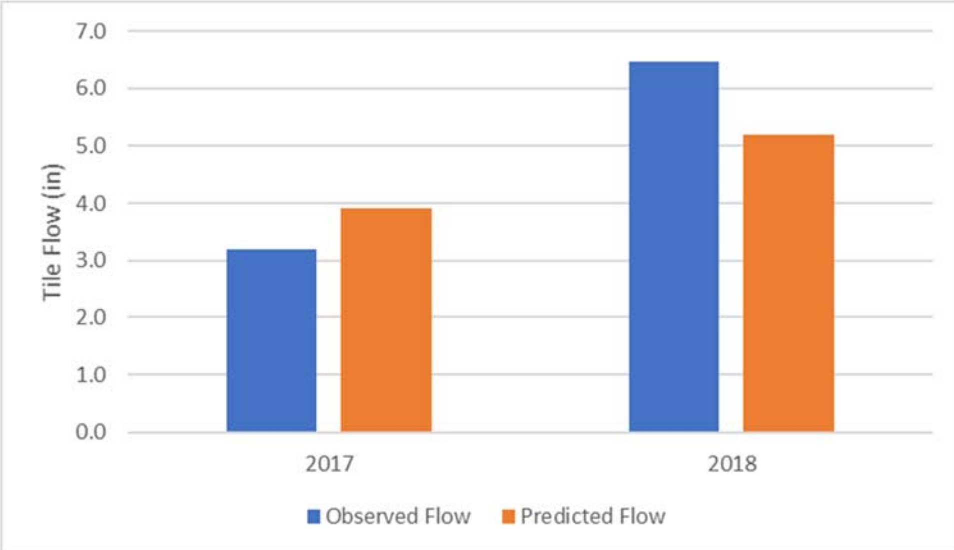

Figure 58. Observed versus model-predicted annual tile flow at JBT18.

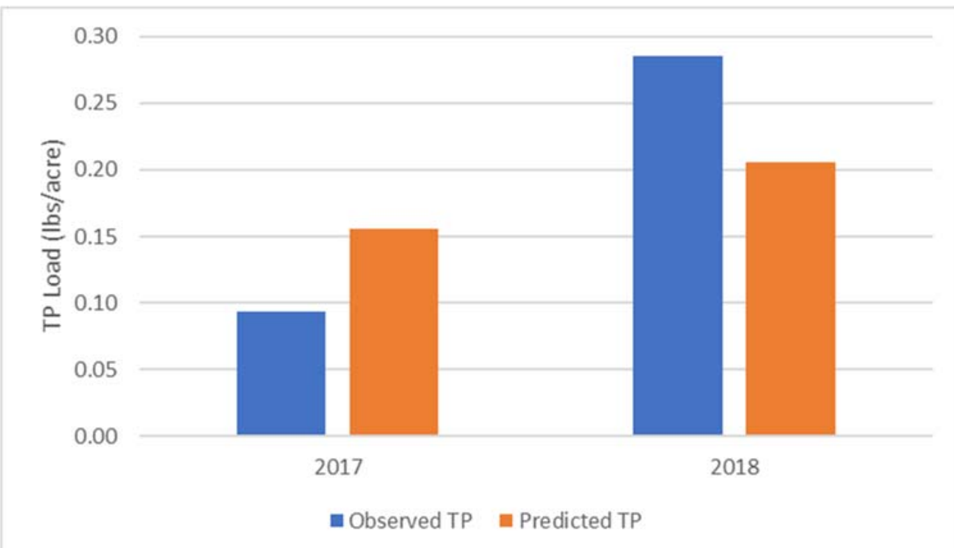

Figure 59. Observed versus model-predicted annual total P at JBT18.

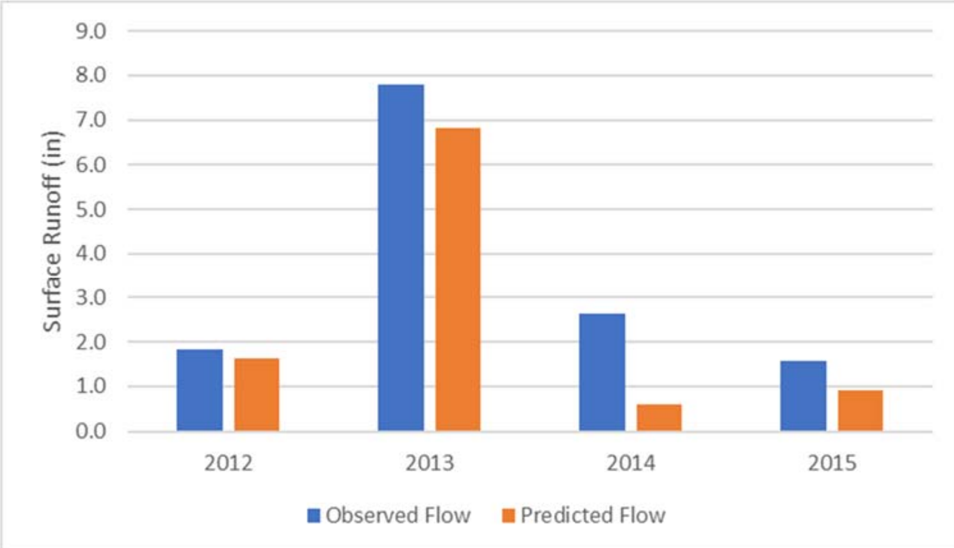

Figure 60. Observed versus model-predicted annual surface runoff (flow) at PAW1.

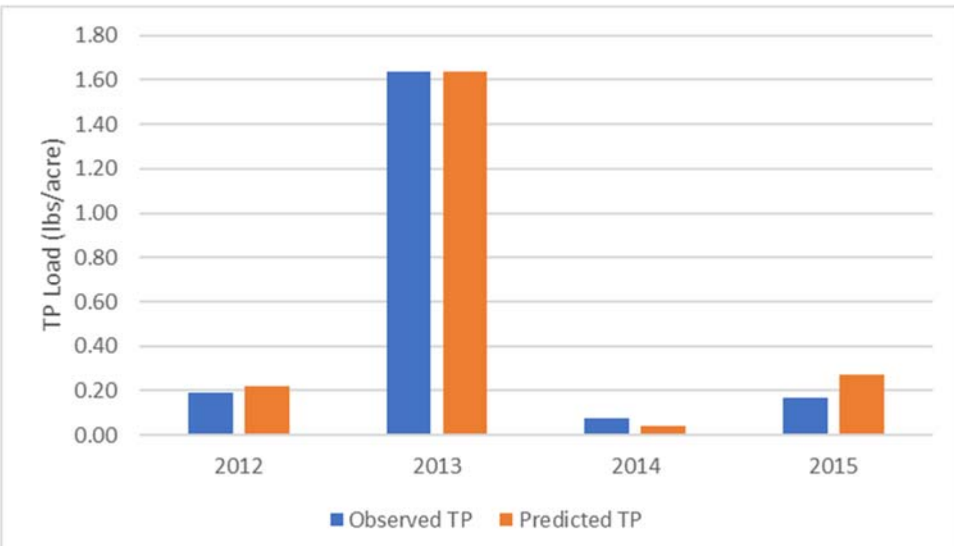

Figure 61. Observed versus model-predicted annual total P at PAW1.

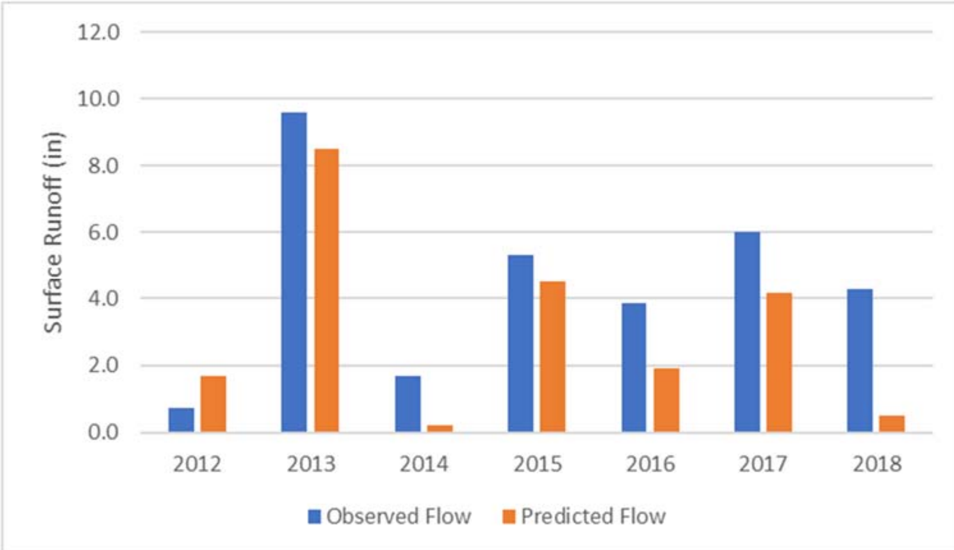

Figure 62. Observed versus model-predicted annual surface runoff (flow) at SHE1.

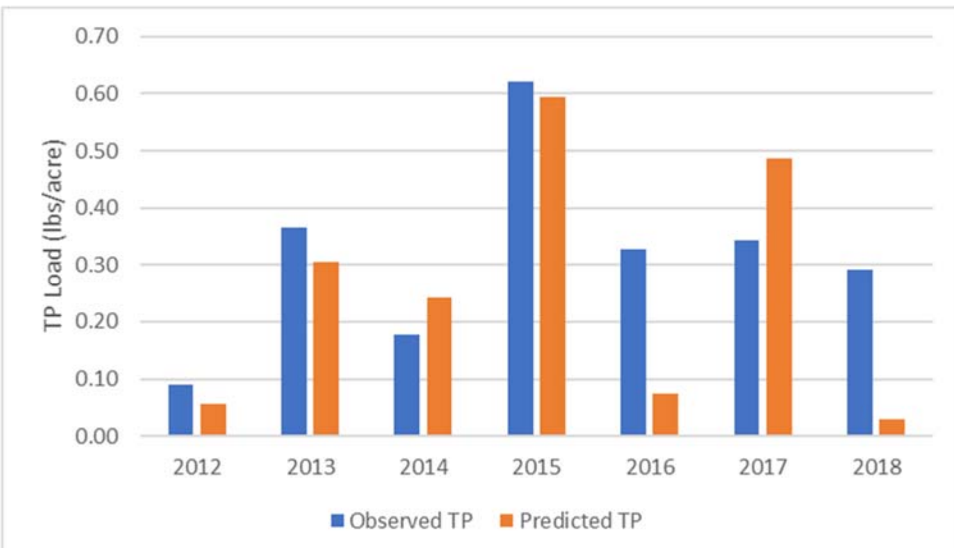

Figure 63. Observed versus model-predicted annual total P at SHE1.

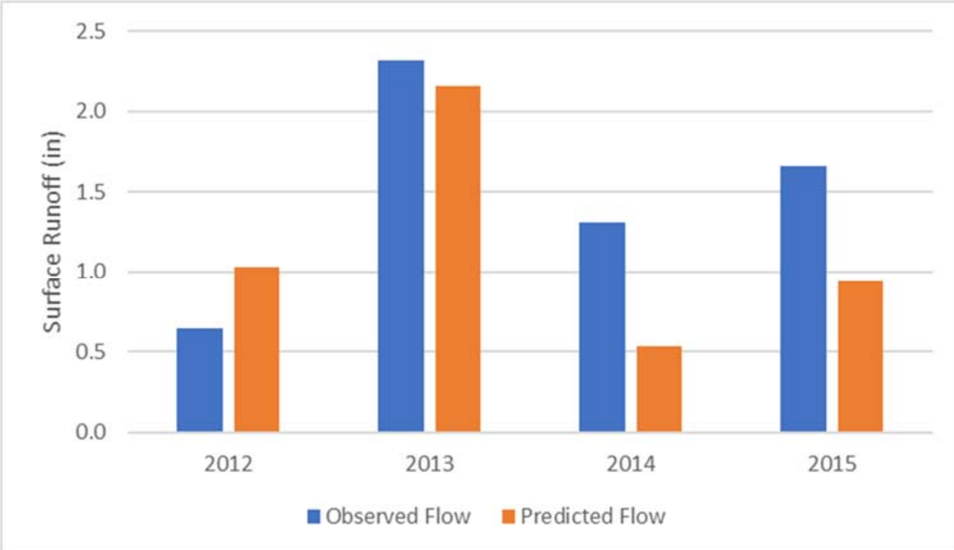

Figure 64. Observed versus model-predicted annual surface runoff (flow) at SHO1.

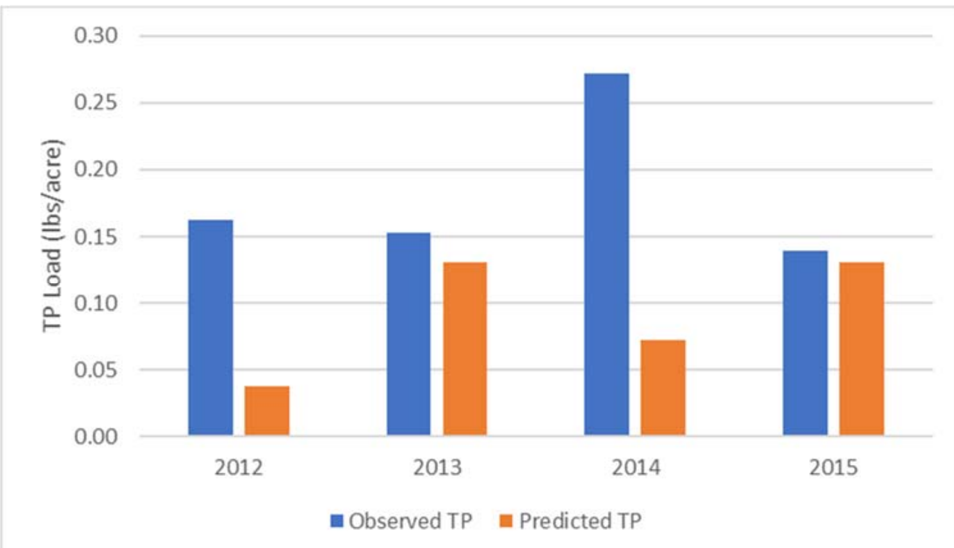

Figure 65. Observed versus model-predicted annual total P at SHO1.

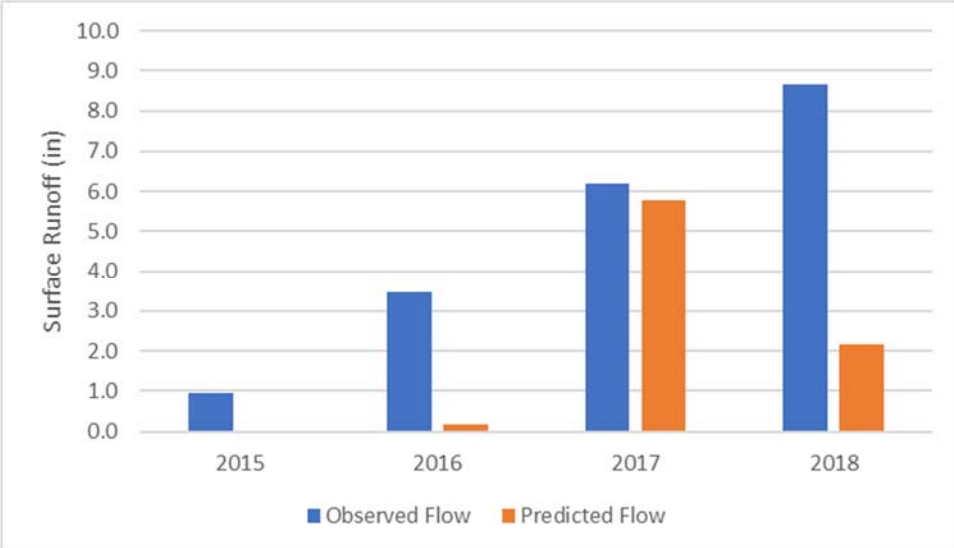

Figure 66. Observed versus model-predicted annual tile flow at M1.

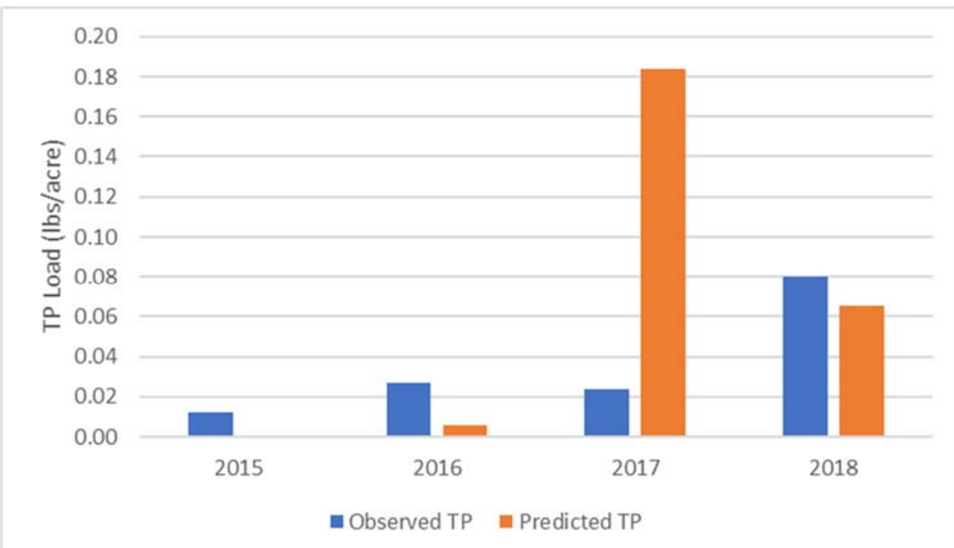

Figure 67. Observed versus model-predicted annual total P in tile flow at M1.

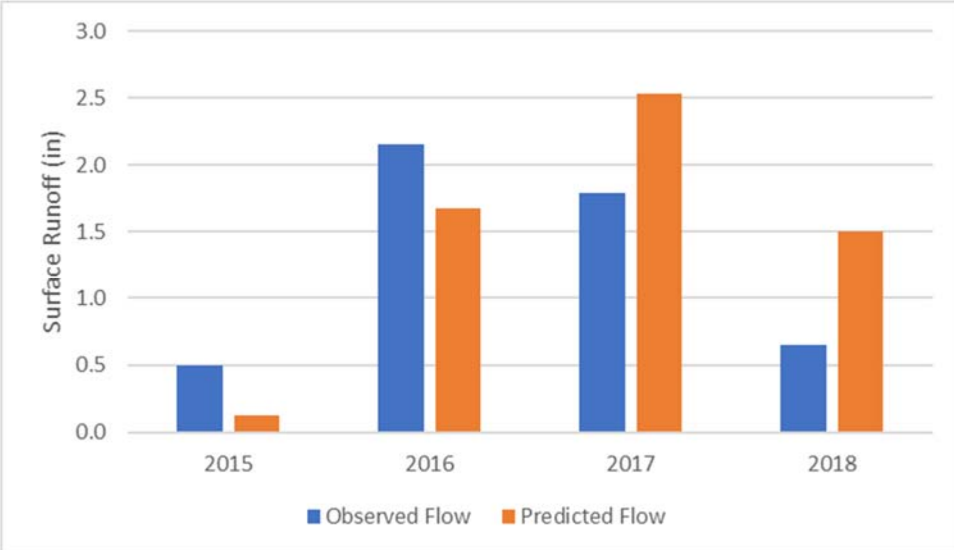

Figure 68. Observed versus model-predicted annual surface runoff (flow) at M1.

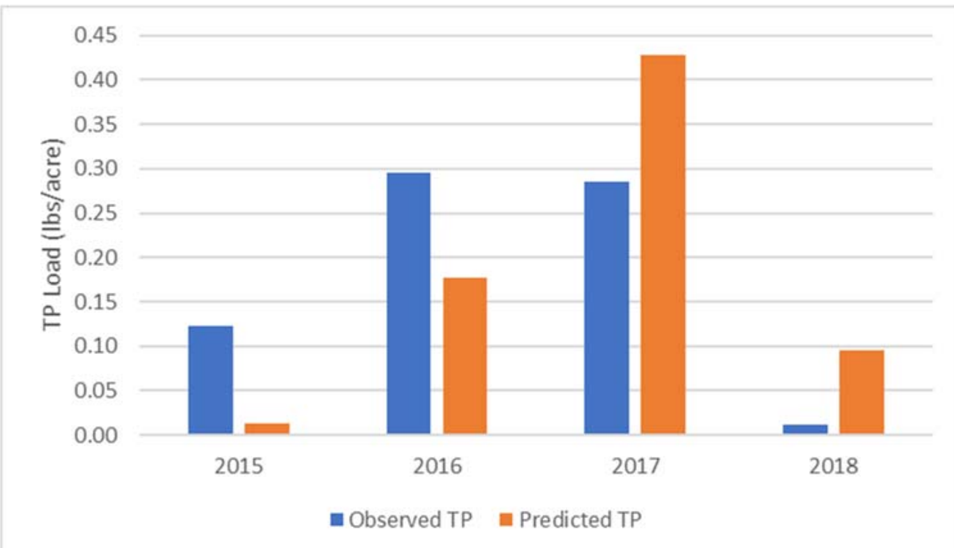

Figure 69. Observed versus model-predicted annual total P in surface runoff at M1.

Appendix C: Cumulative Distribution Plots of Model-Predicted Total P Percent Bias, Soils Monte Carlo Analysis with Global Parameterization.

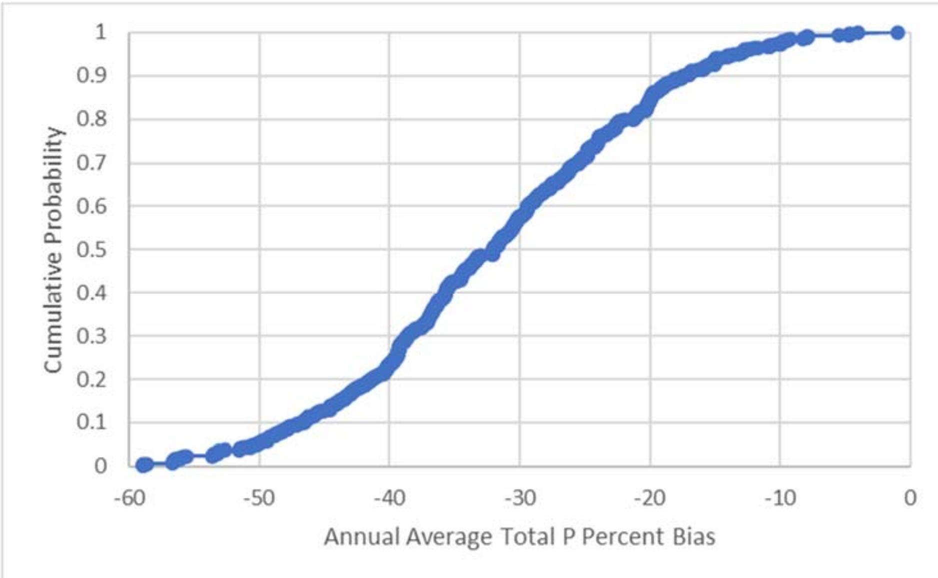

Figure 70. Cumulative distribution of average annual total P percent bias for CHA1.

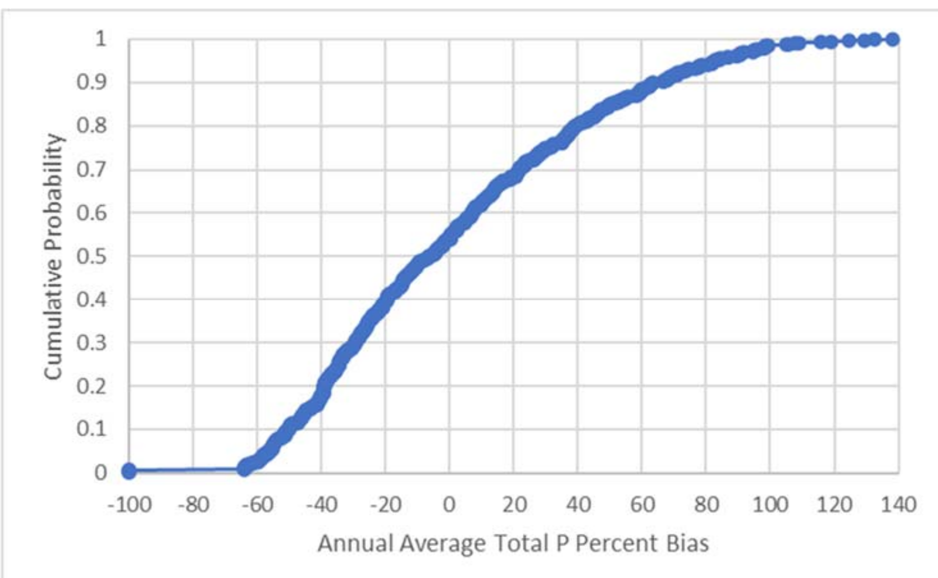

Figure 71. Cumulative distribution of total P percent bias for FER1.

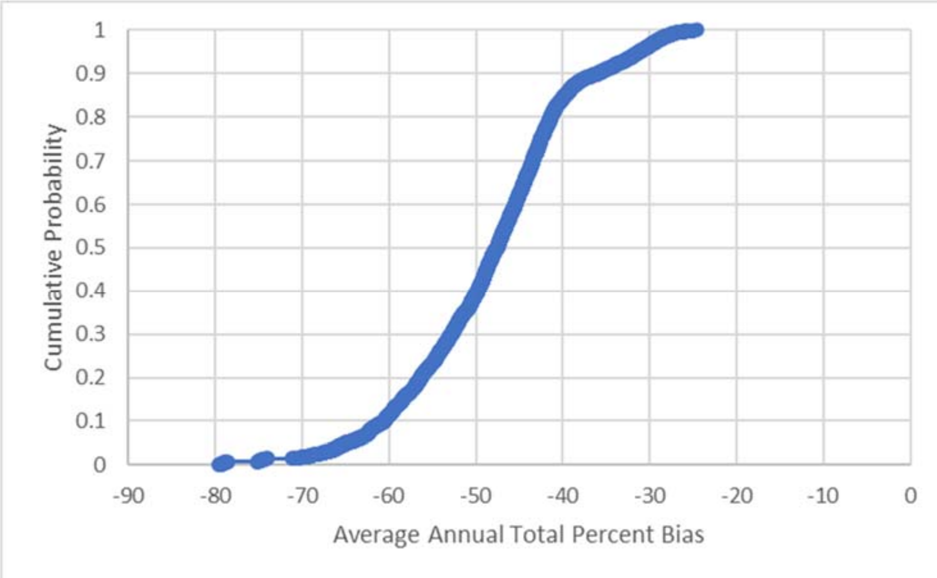

Figure 72. Cumulative distribution of total P percent bias for JBT01.

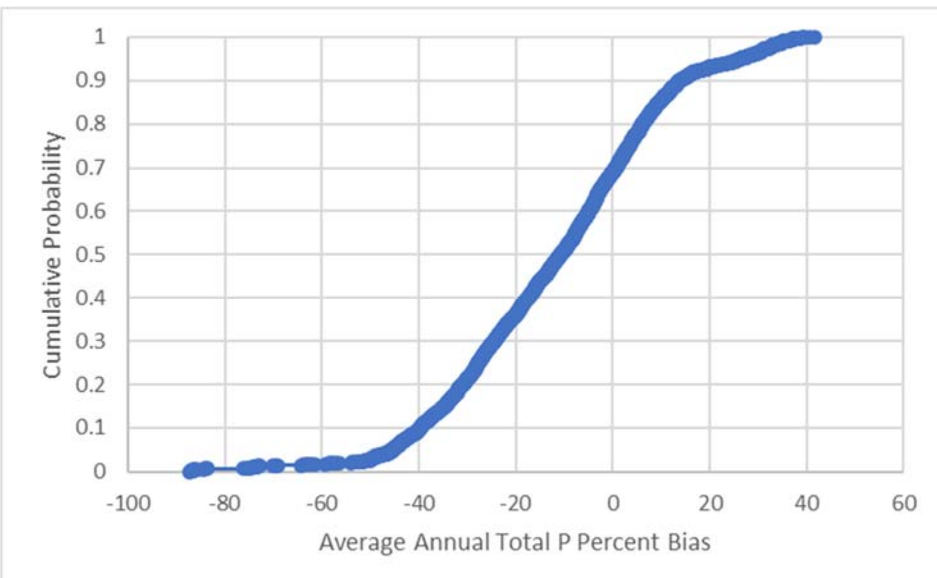

Figure 73. Cumulative distribution of total P percent bias for JBT04.

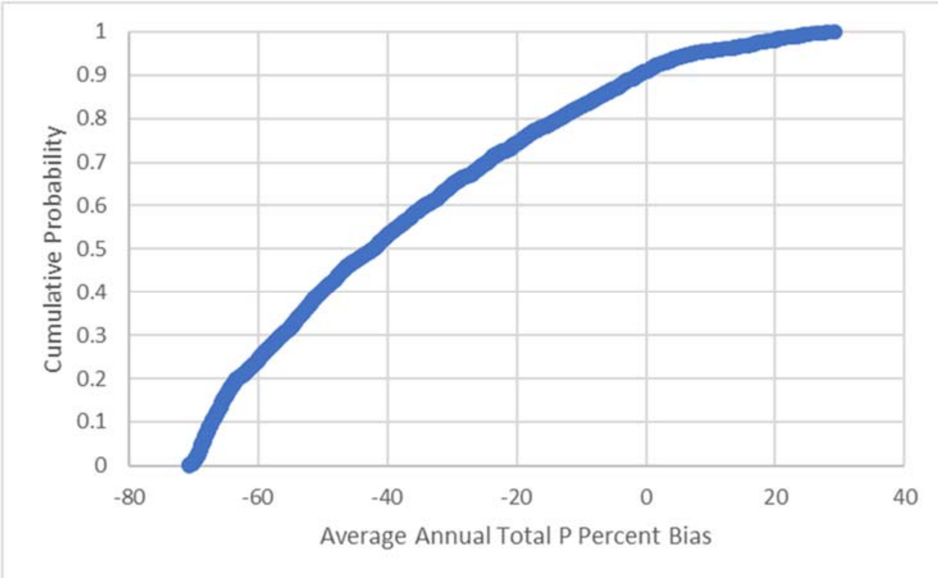

Figure 74. Cumulative distribution of total P percent bias for JBT05.

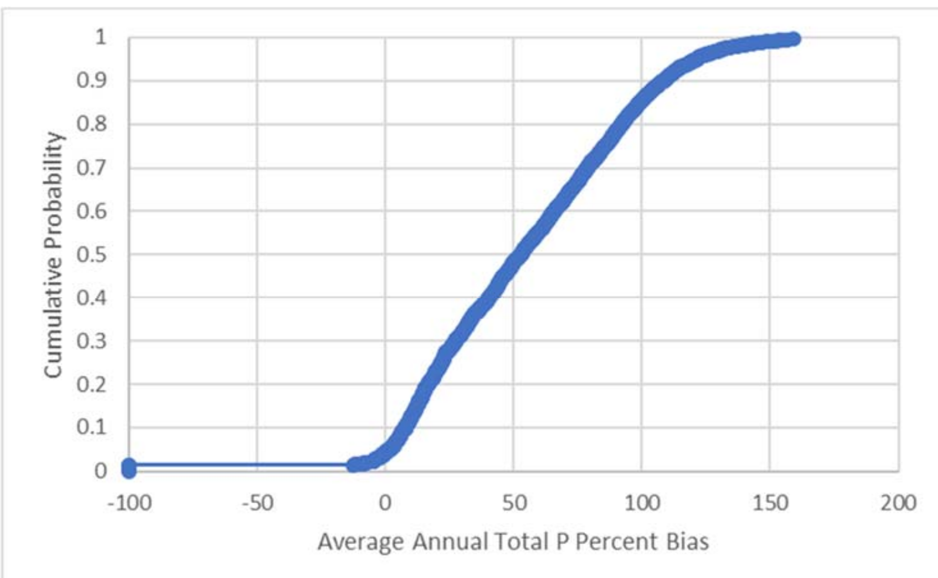

Figure 75. Cumulative distribution of total P percent bias for JBT07.

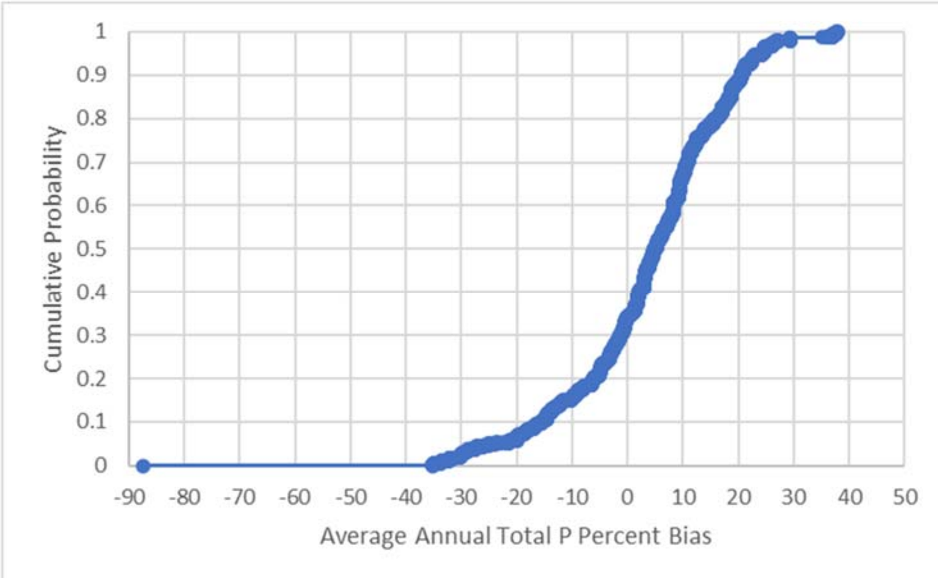

Figure 76. Cumulative distribution of total P percent bias for JBT11.

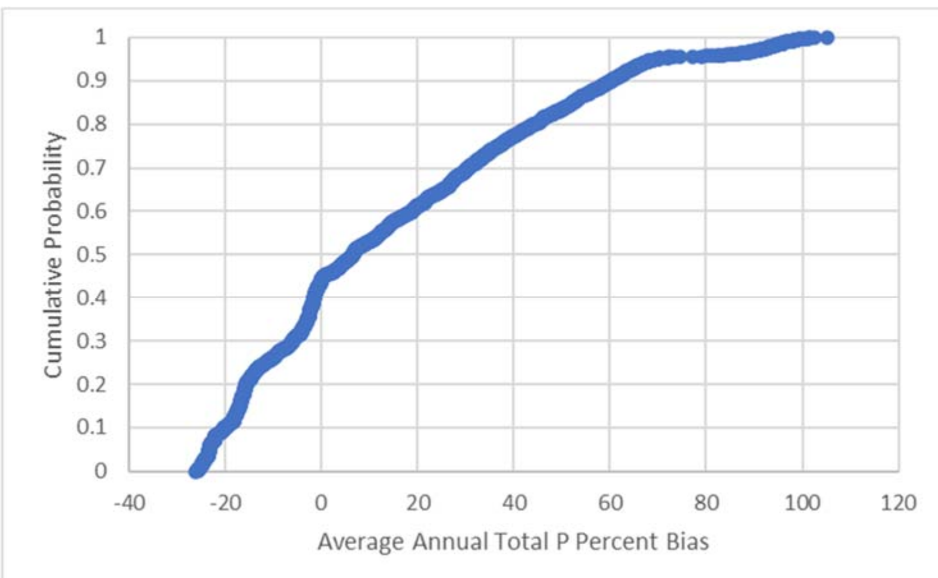

Figure 77. Cumulative distribution of total P percent bias for JBT18.

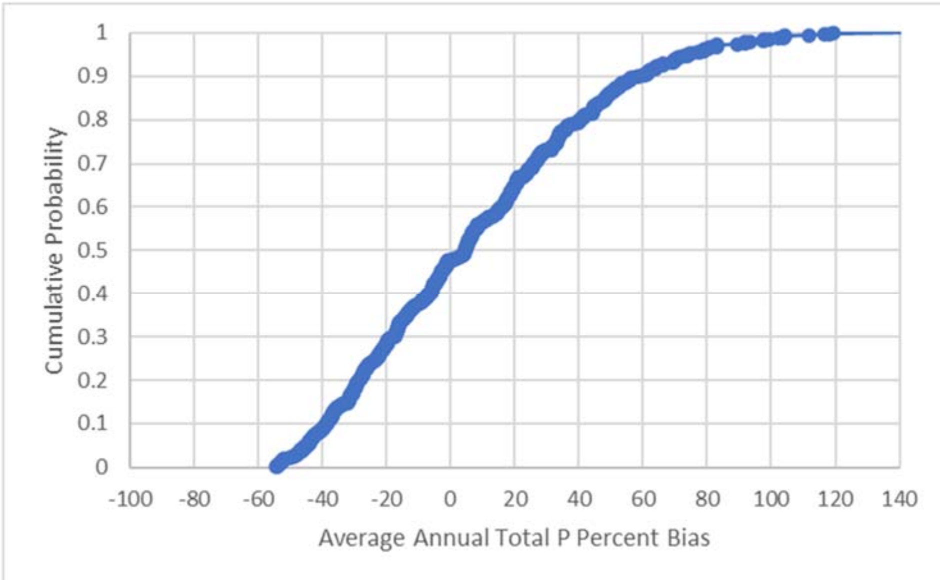

Figure 78. Cumulative distribution of total P percent bias for PAW1.

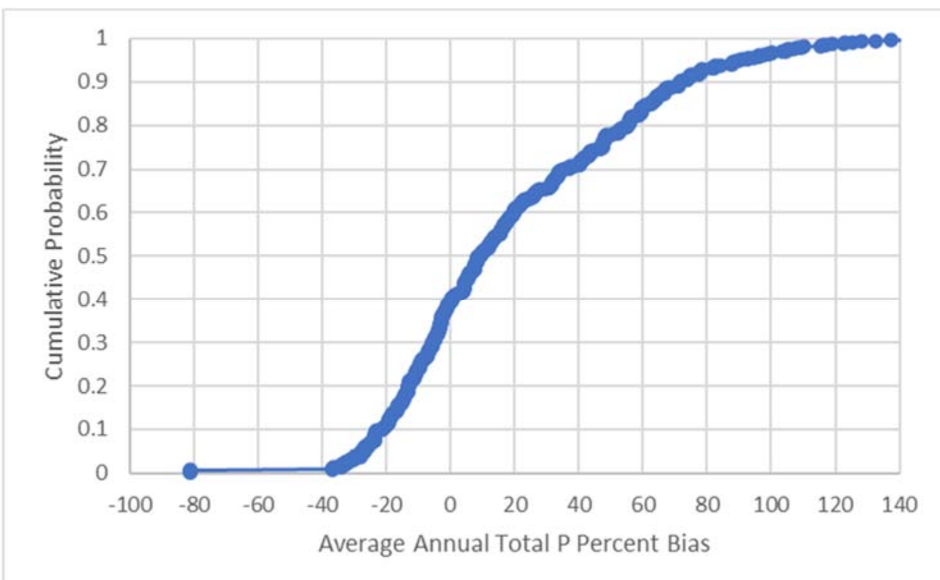

Figure 79. Cumulative distribution of total P percent bias for SHE1.

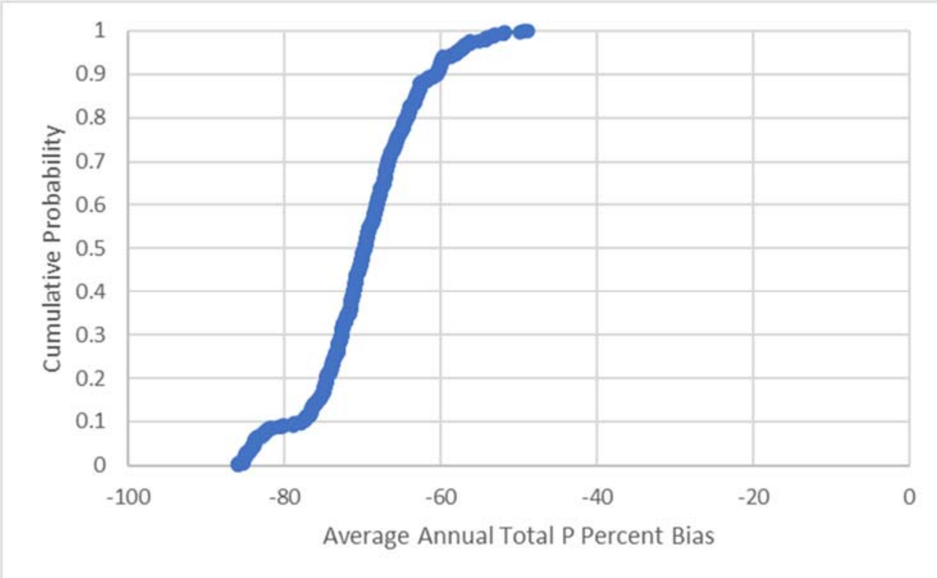

Figure 80. Cumulative distribution of total P percent bias for SHO1.

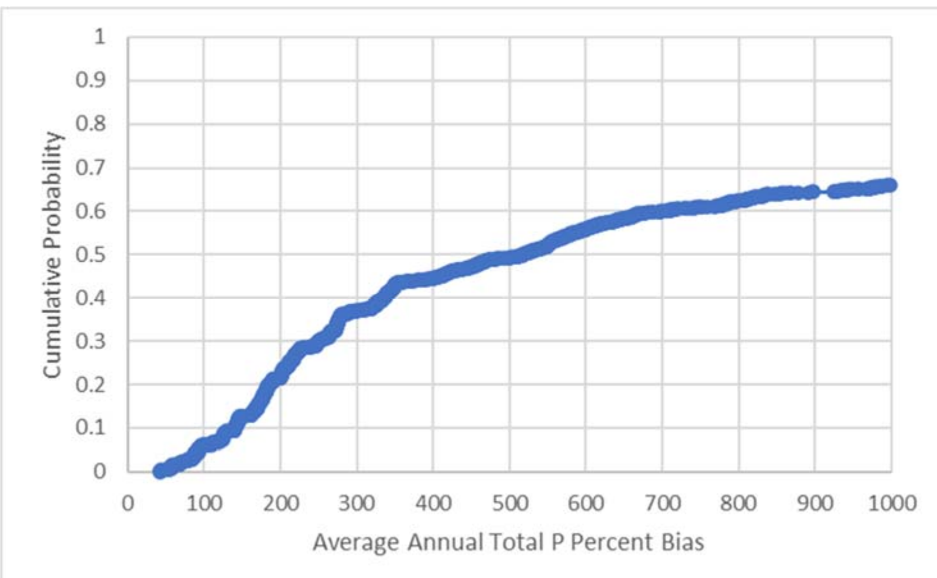

Figure 81. Cumulative distribution of total P percent bias for M1 tile.

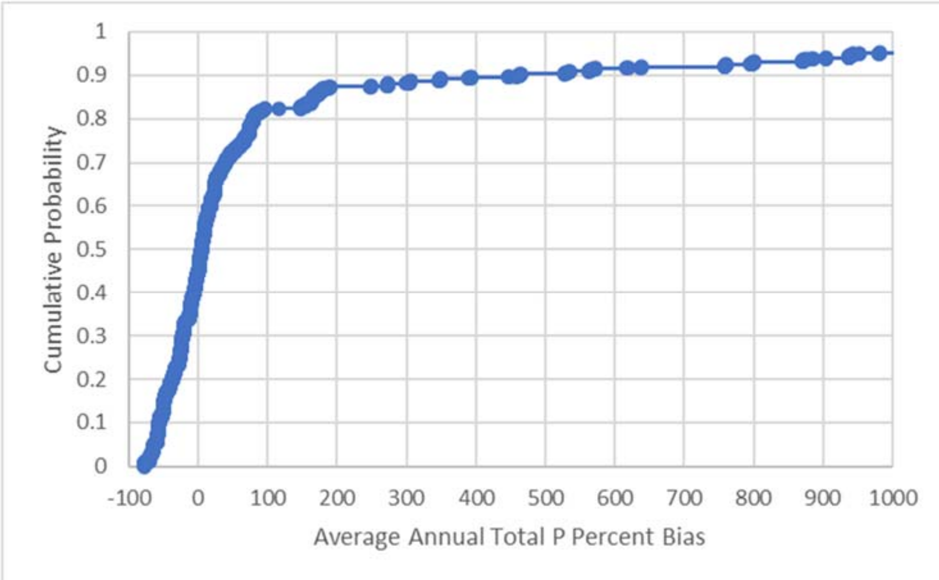

Figure 82. Cumulative distribution of total P percent bias for M1 surface runoff.

Appendix D: Time Series Plots of Annual Flow and Total P Based on Site-Specific Parameterization Simulations, Representative Soils Parameters

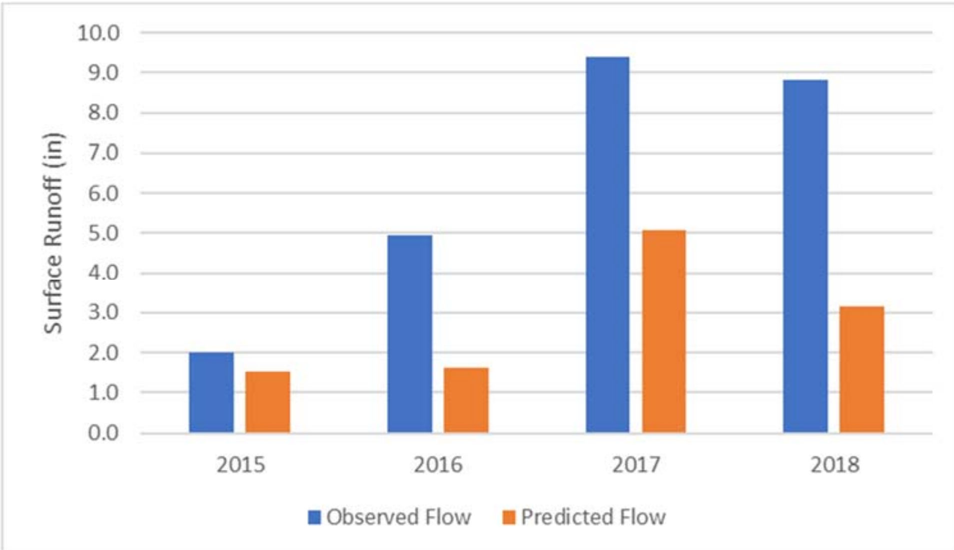

Figure 83. Observed versus model-predicted annual surface runoff (flow) at CHA1.

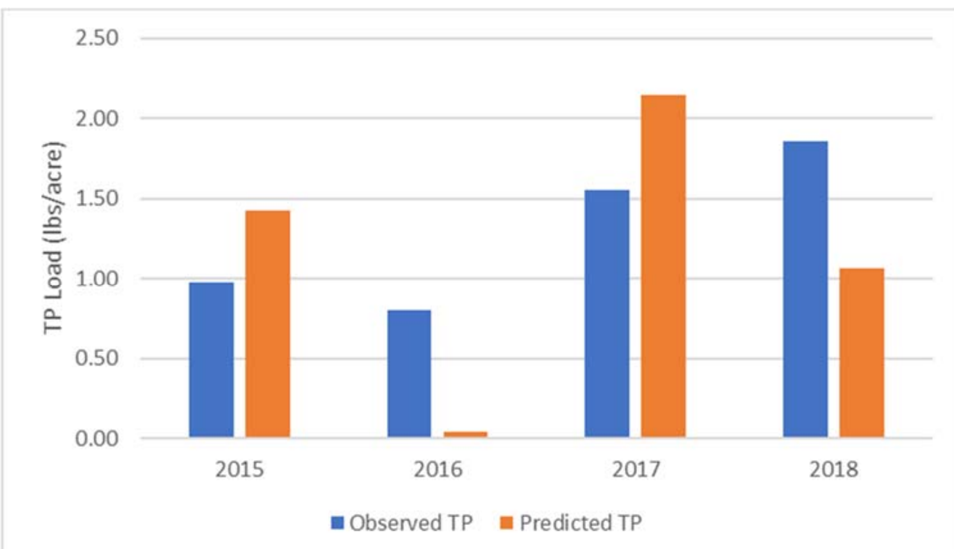

Figure 84. Observed versus model-predicted annual total P at CHA1.

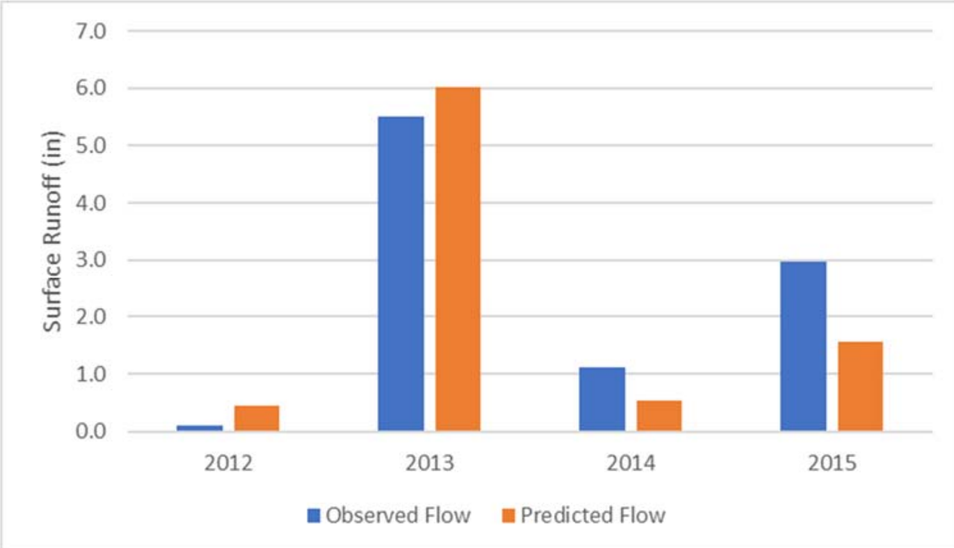

Figure 85. Observed versus model-predicted annual surface runoff (flow) at FER1.

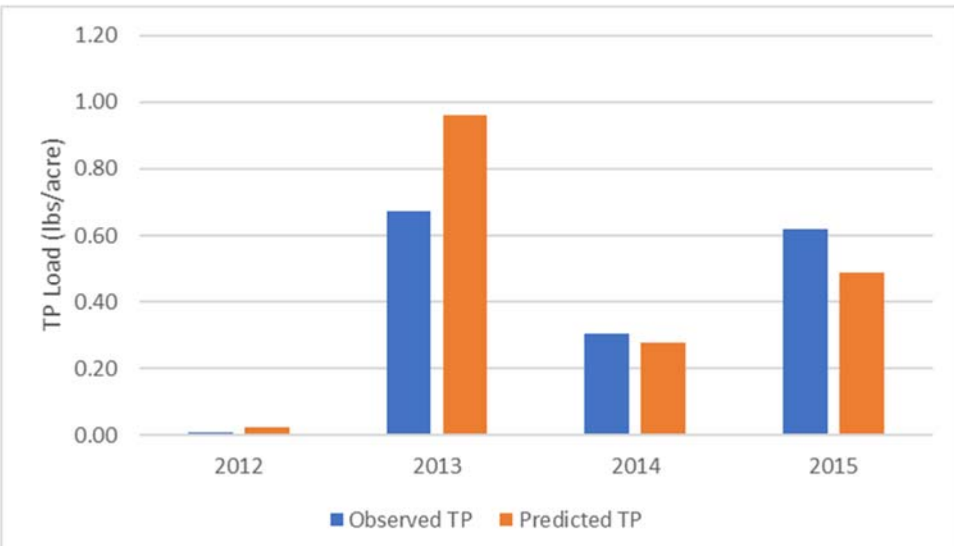

Figure 86. Observed versus model-predicted annual total P at FER1.

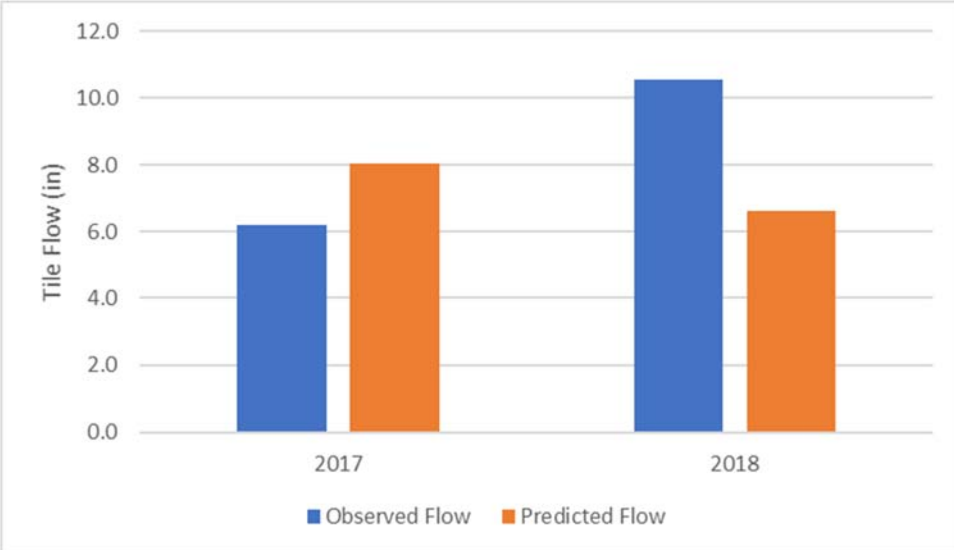

Figure 87. Observed versus model-predicted annual tile flow at JBT01.

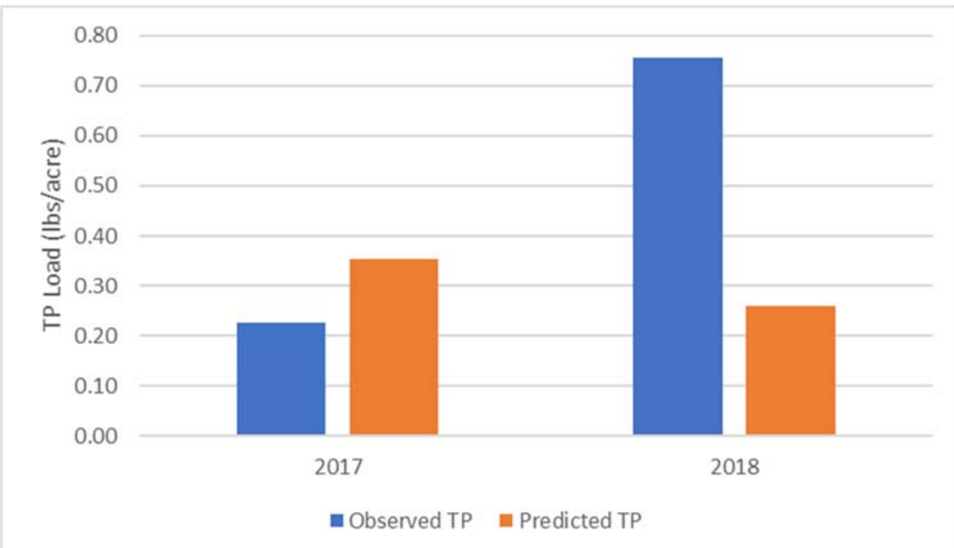

Figure 88. Observed versus model-predicted annual total P at JBT01.

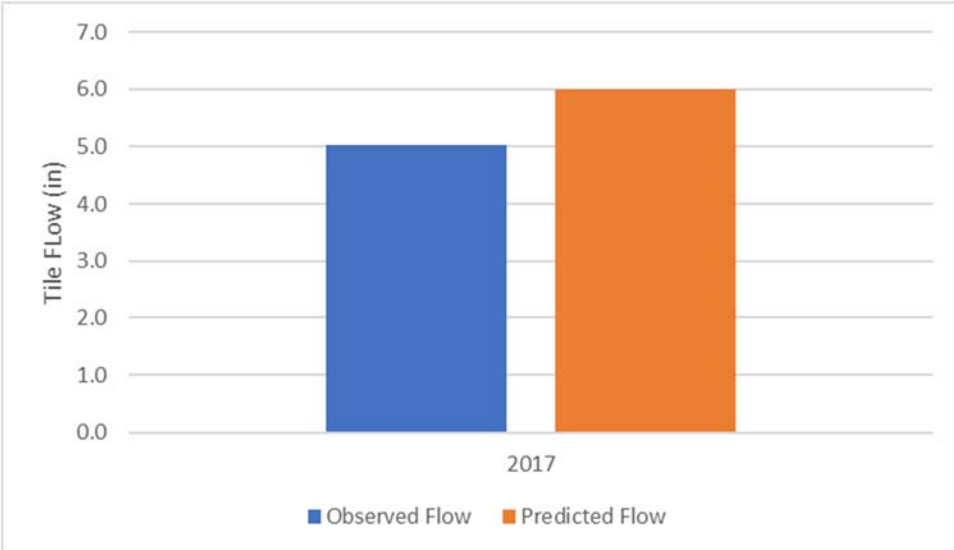

Figure 89. Observed versus model-predicted annual tile flow at JBT04.

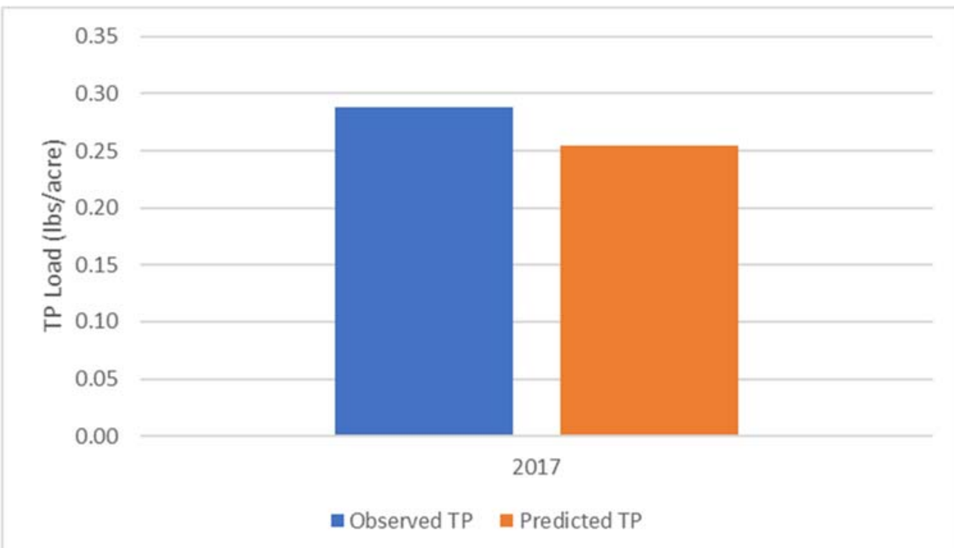

Figure 90. Observed versus model-predicted annual total P at JBT04.

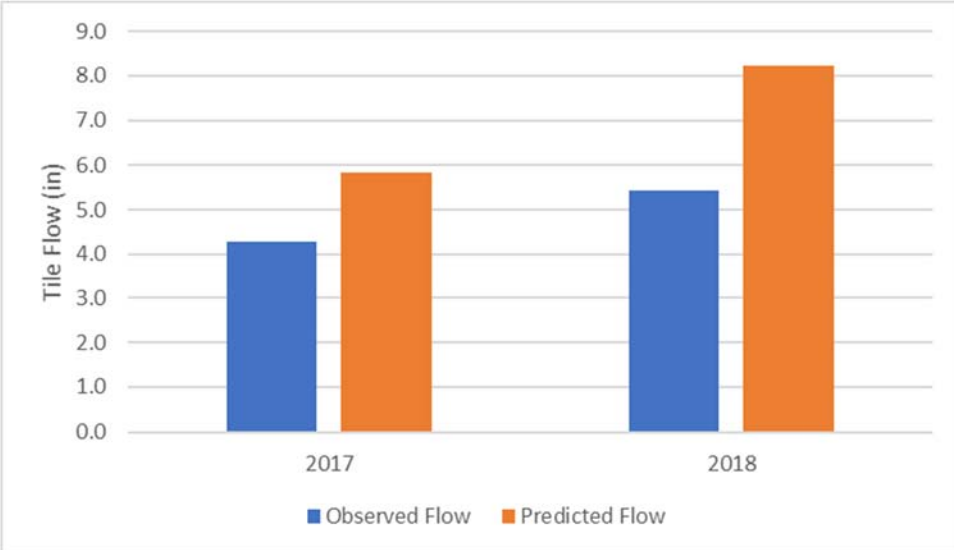

Figure 91. Observed versus model-predicted annual tile flow at JBT05.

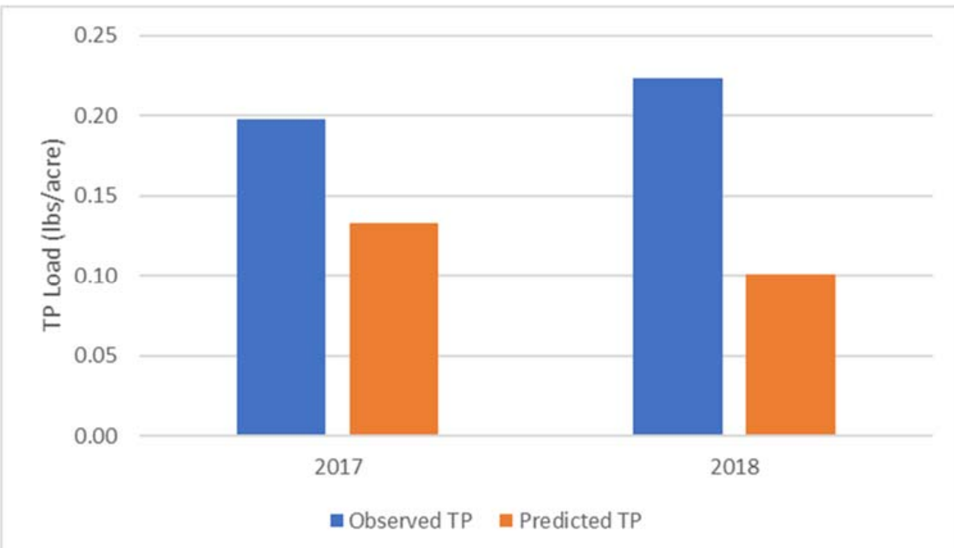

Figure 92. Observed versus model-predicted annual total P at JBT05.

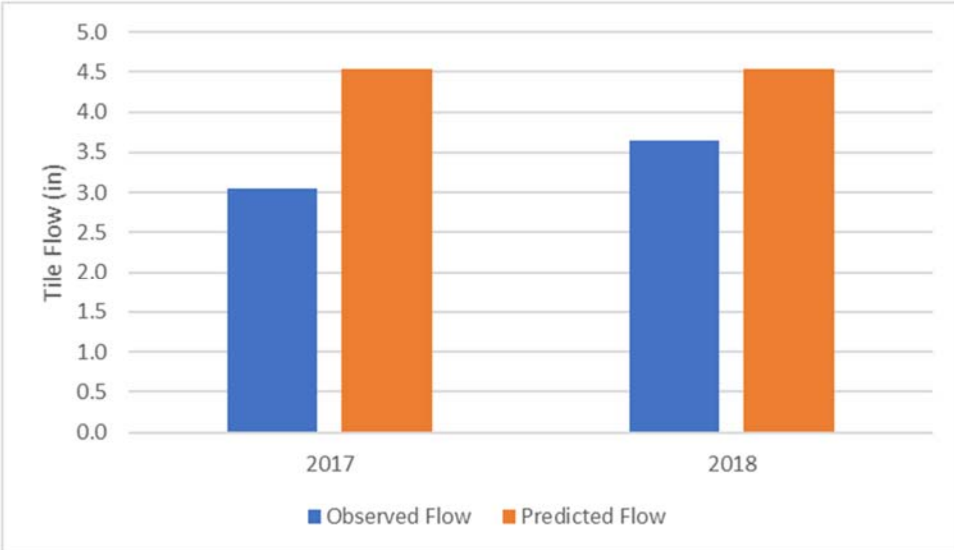

Figure 93. Observed versus model-predicted annual tile flow at JBT07.

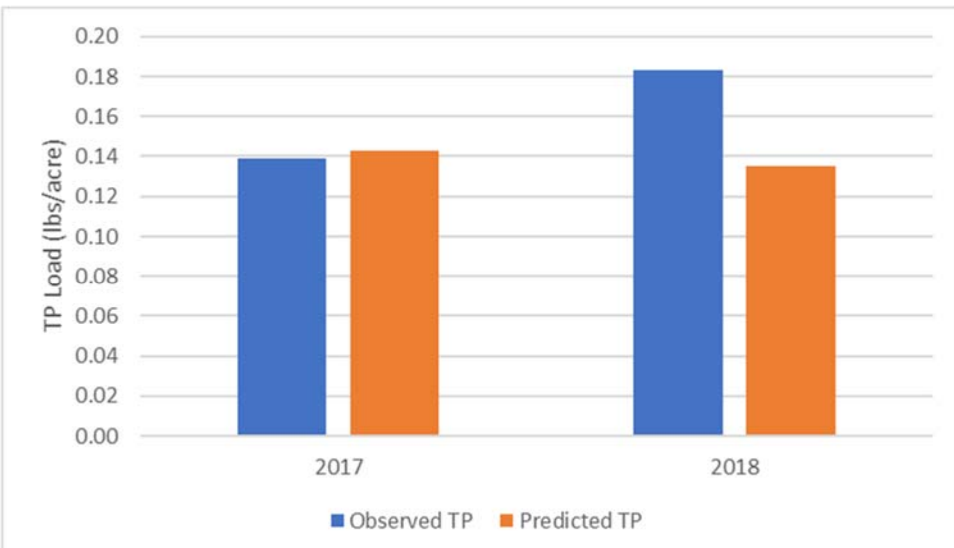

Figure 94. Observed versus model-predicted annual total P at JBT07.

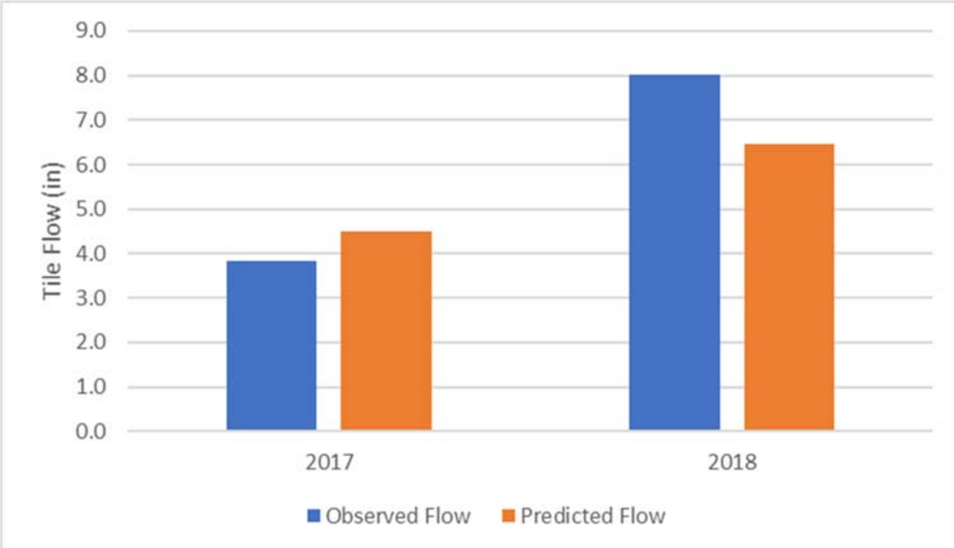

Figure 95. Observed versus model-predicted annual tile flow at JBT11.

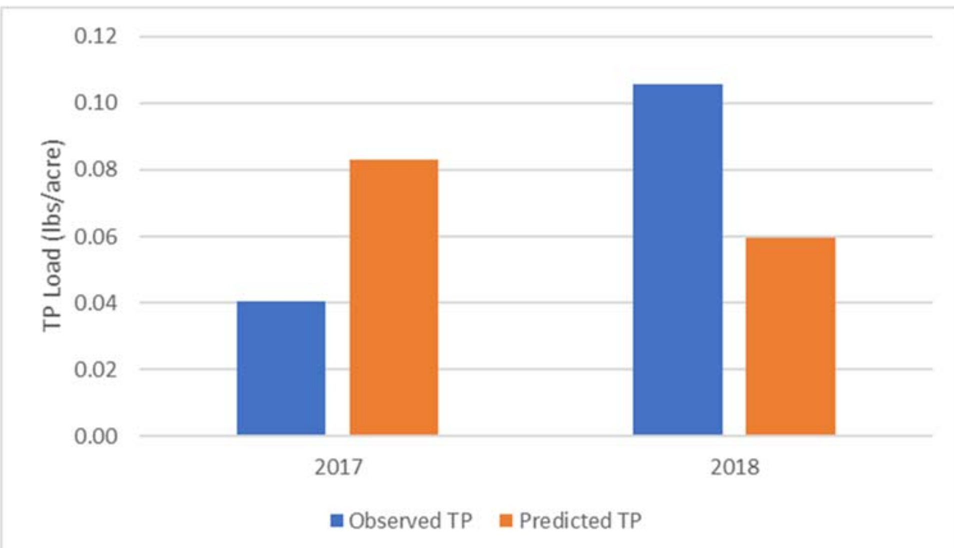

Figure 96. Observed versus model-predicted annual total P at JBT11.

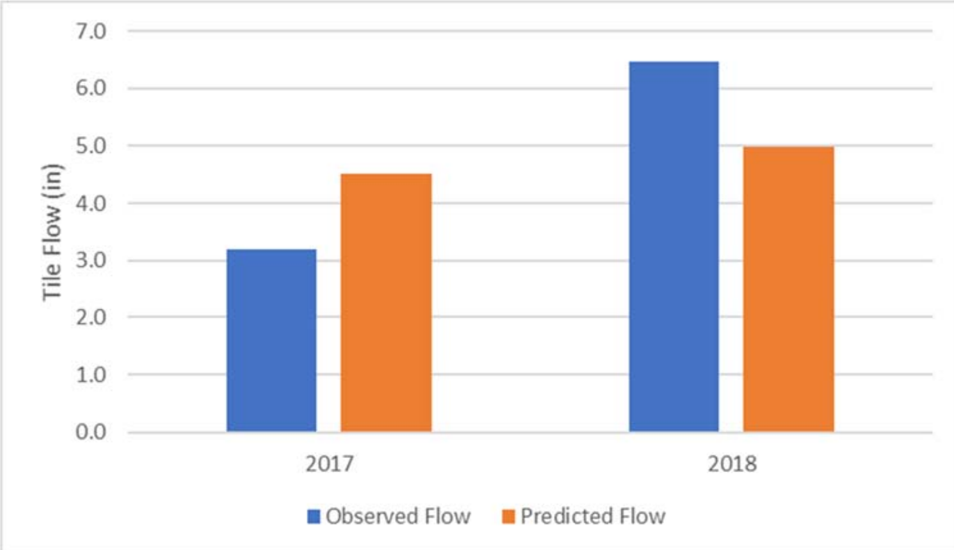

Figure 97. Observed versus model-predicted annual tile flow at JBT18.

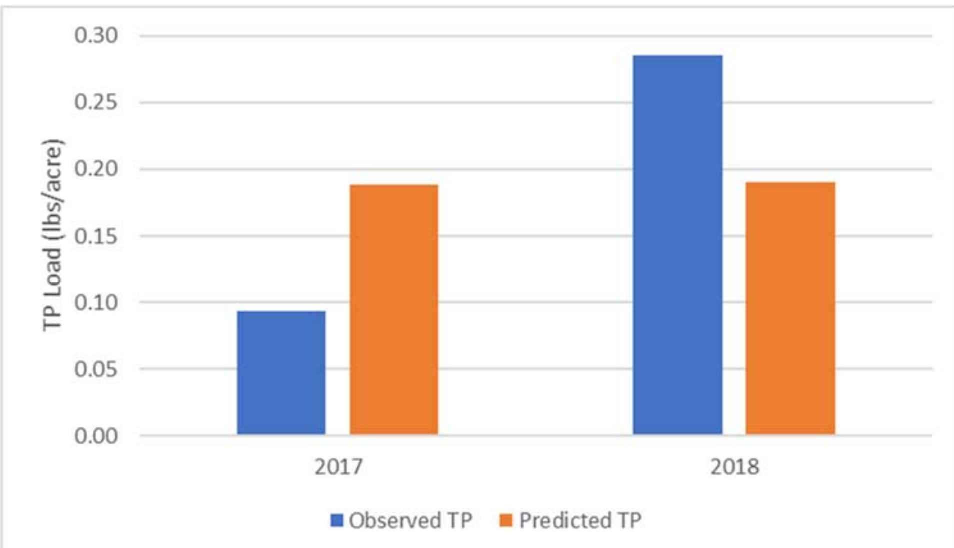

Figure 98. Observed versus model-predicted annual total P at JBT18.

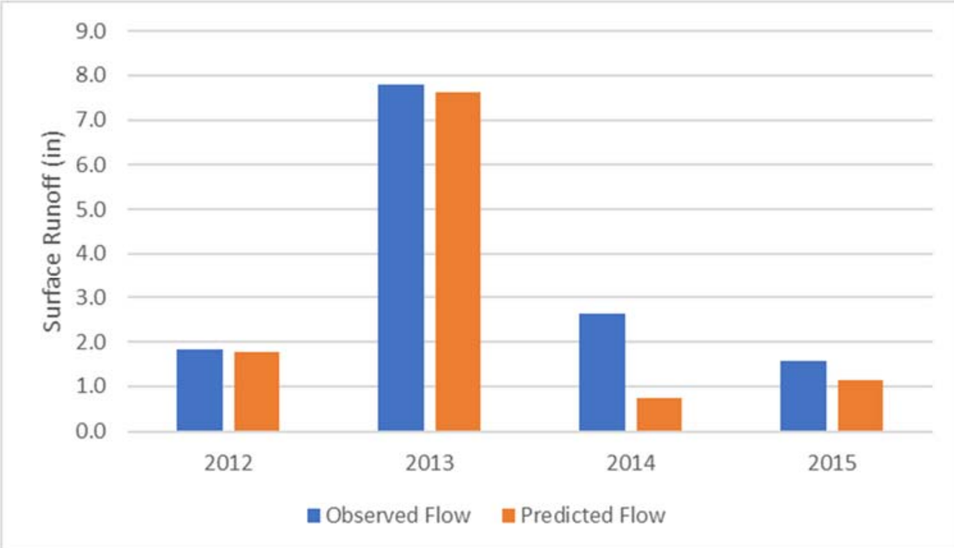

Figure 99. Observed versus model-predicted annual surface runoff (flow) at PAW1.

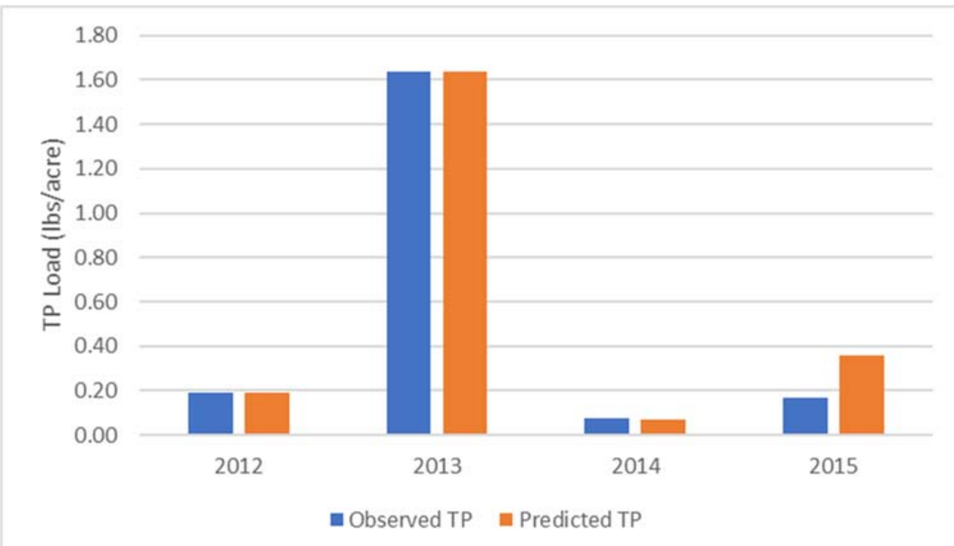

Figure 100. Observed versus model-predicted annual total P at PAW1.

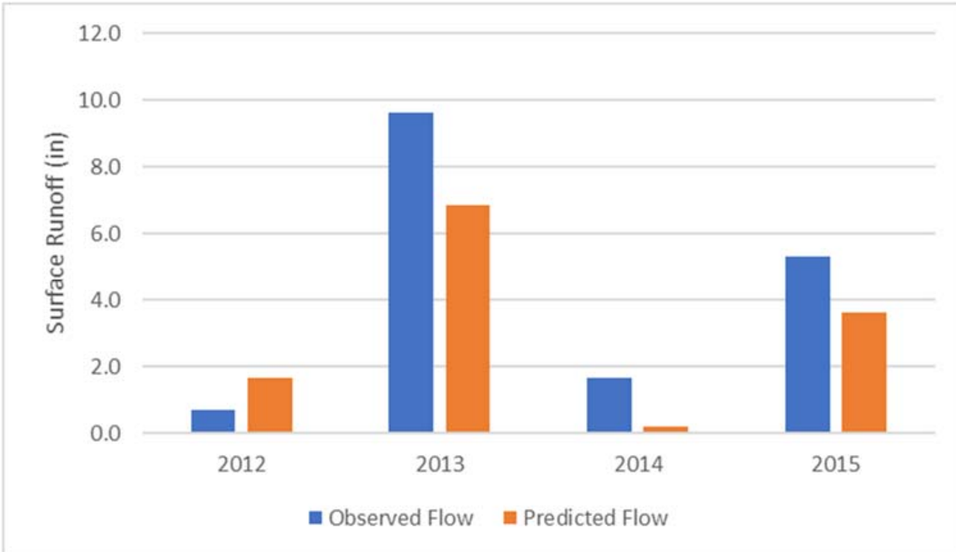

Figure 101. Observed versus model-predicted annual surface runoff (flow) at SHE1.

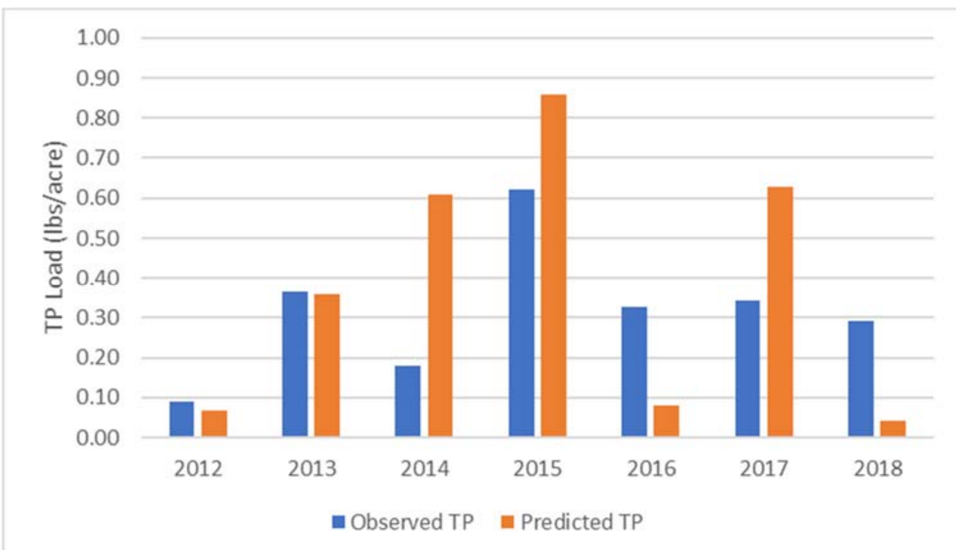

Figure 102. Observed versus model-predicted annual total P at SHE1.

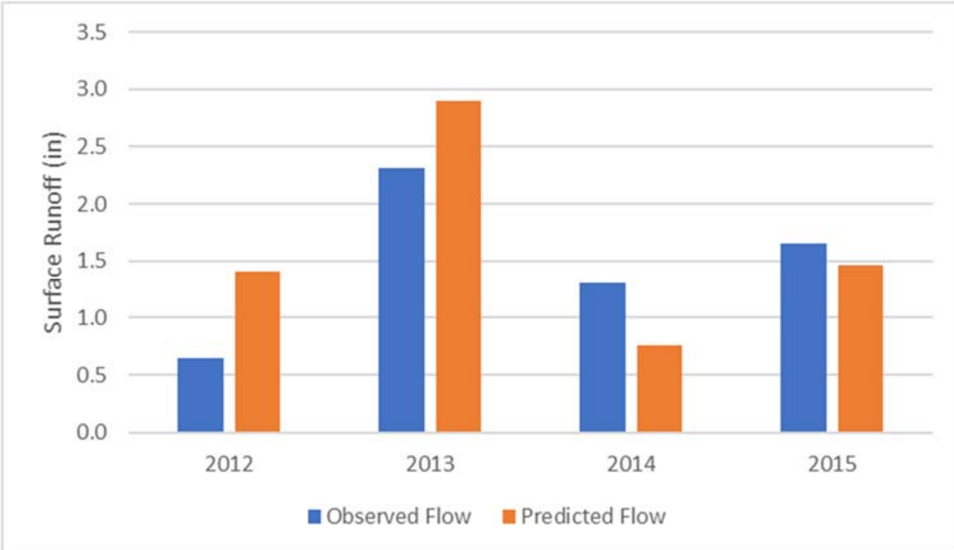

Figure 103. Observed versus model-predicted annual surface runoff (flow) at SHO1.

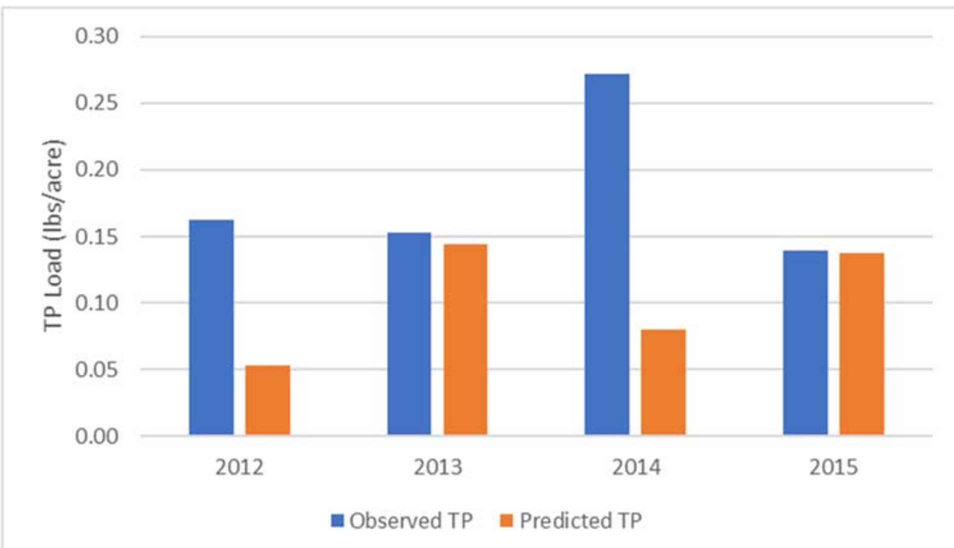

Figure 104. Observed versus model-predicted annual total P at SHO1.

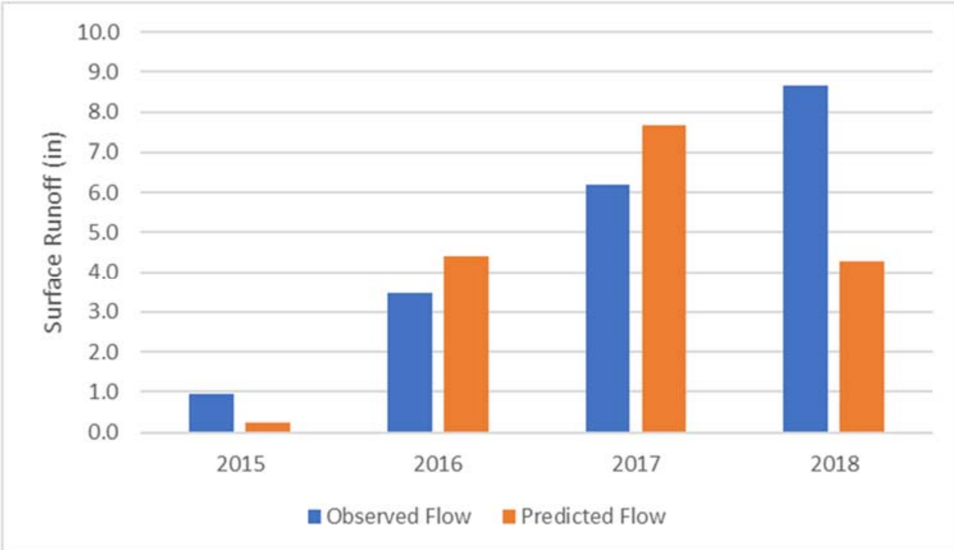

Figure 105. Observed versus model-predicted annual tile flow at M1.

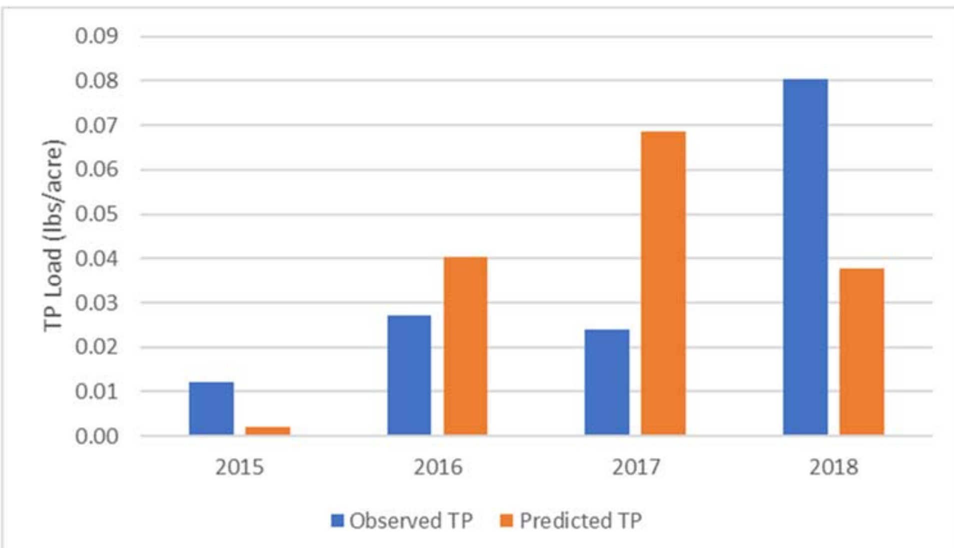

Figure 106. Observed versus model-predicted annual total P in tile drainage at M1.

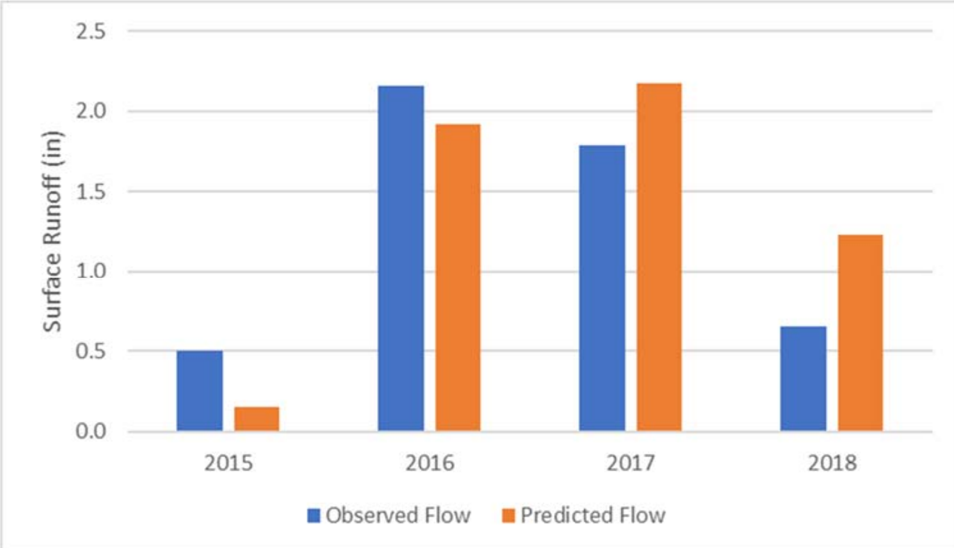

Figure 107. Observed versus model-predicted annual surface runoff (flow) at M1.

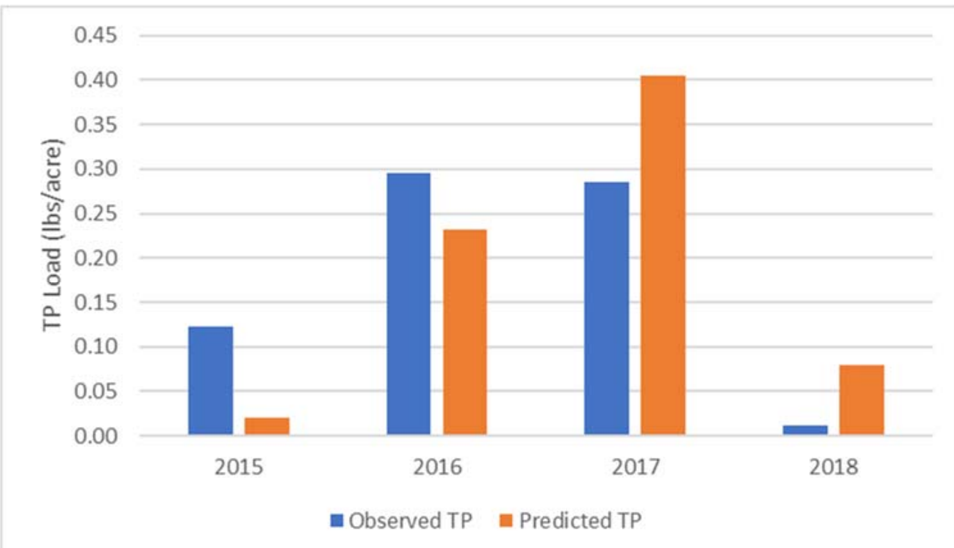

Figure 108. Observed versus model-predicted annual total P in surface runoff at M1.

Appendix E: Time Series Plots of Annual Flow and Total P Based on Site-Specific Parameterization Simulations, Best Soils Parameters

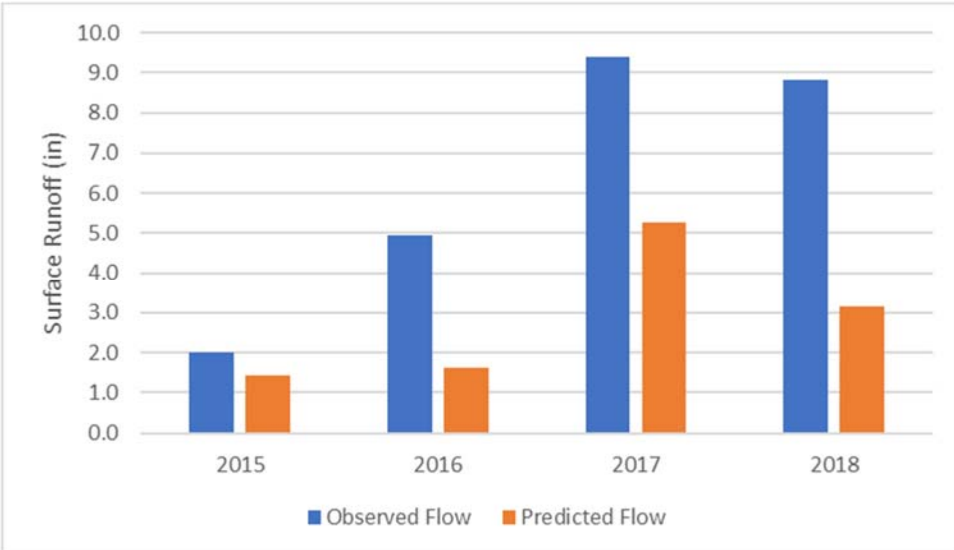

Figure 109. Observed versus model-predicted annual surface runoff (flow) at CHA1.

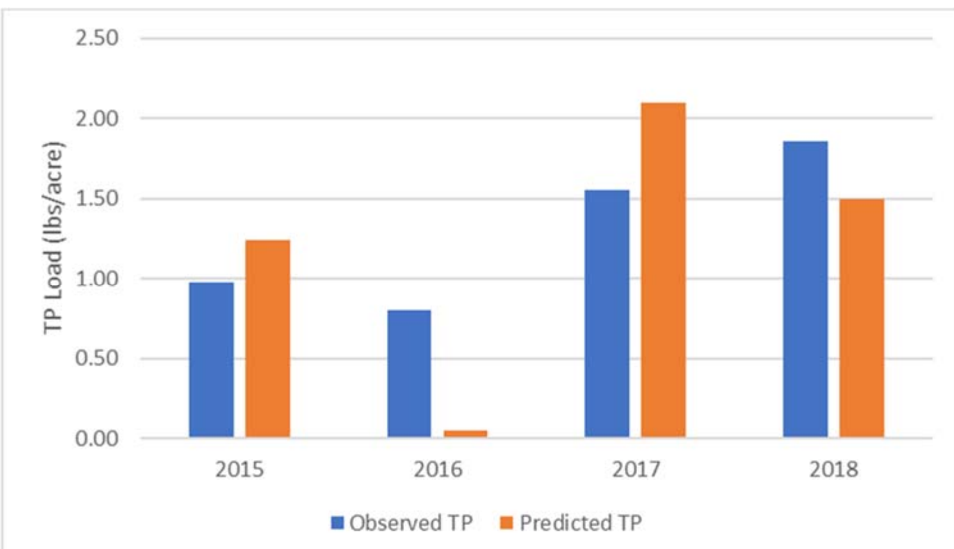

Figure 110. Observed versus model-predicted annual total P at CHA1.

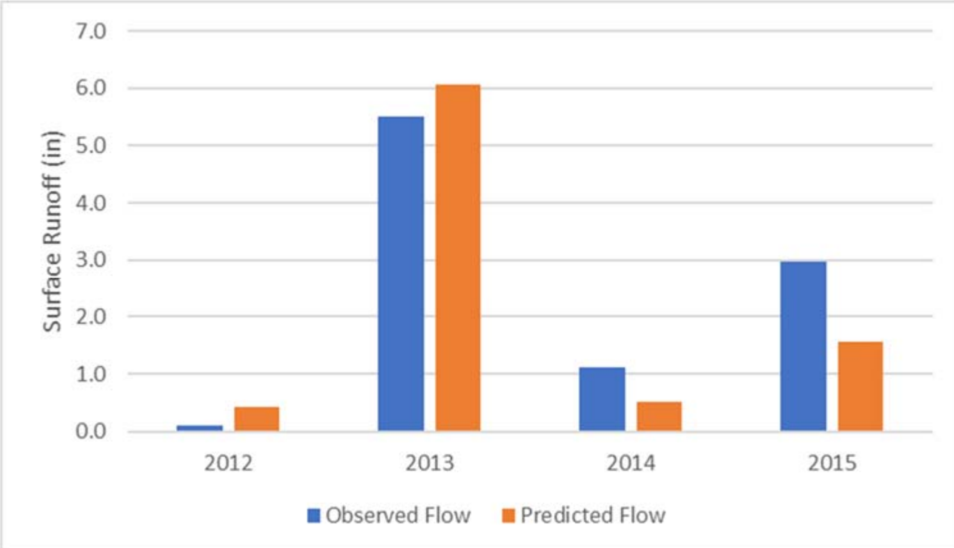

Figure 111. Observed versus model-predicted annual surface runoff (flow) at FER1.

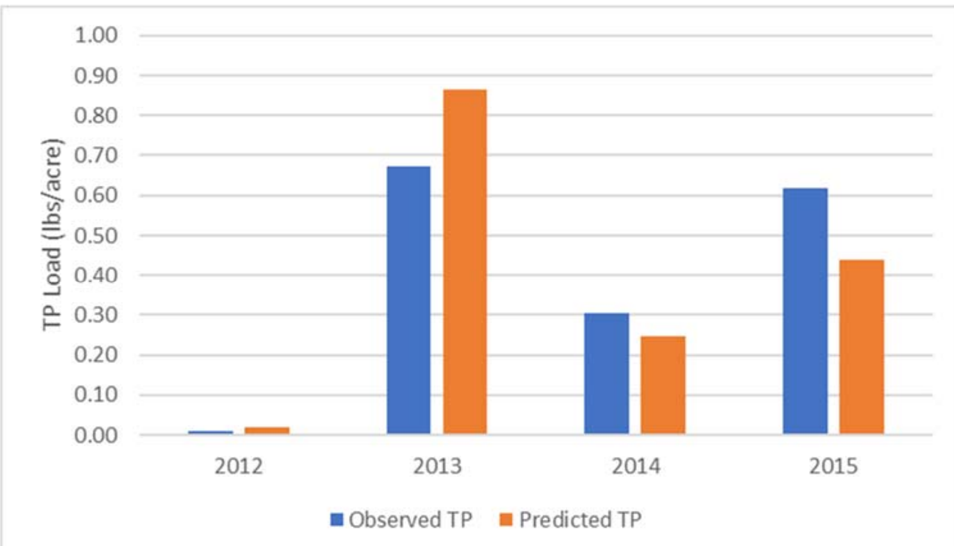

Figure 112. Observed versus model-predicted annual total P at FER1.

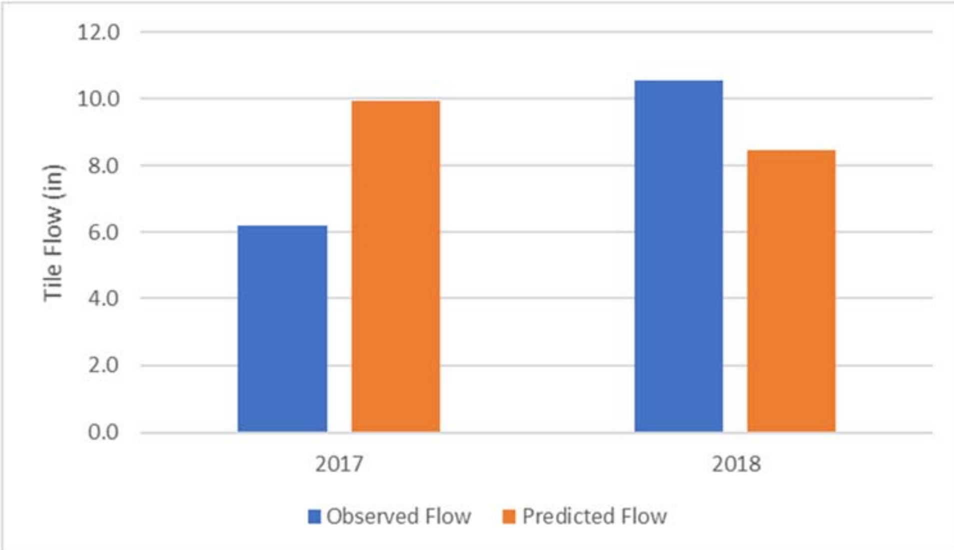

Figure 113. Observed versus model-predicted annual tile flow at JBT01.

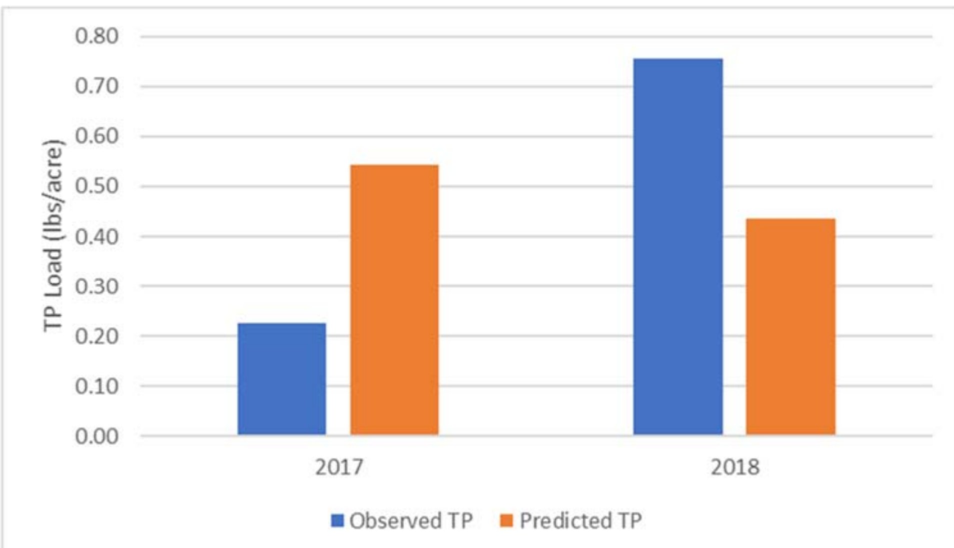

Figure 114. Observed versus model-predicted annual total P at JBT01.

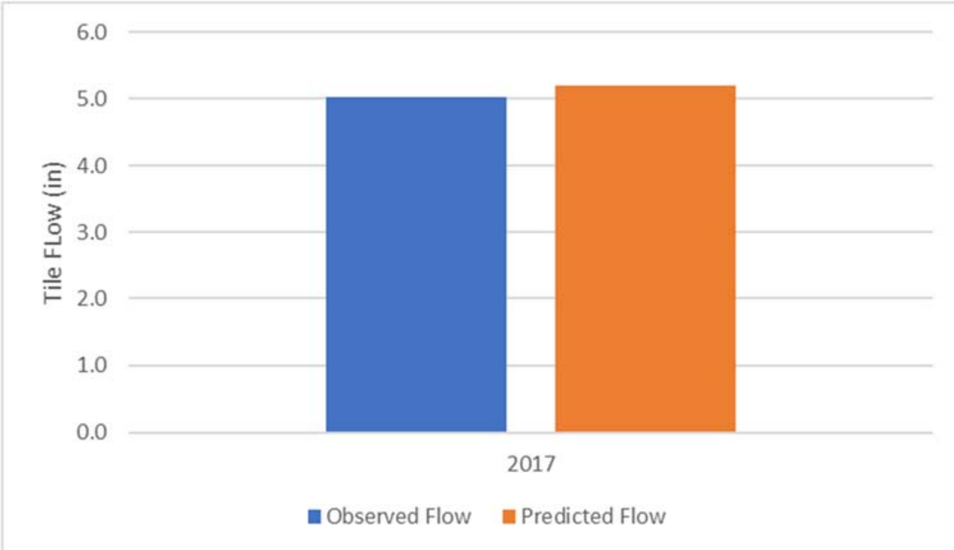

Figure 115. Observed versus model-predicted annual tile flow at JBT04.

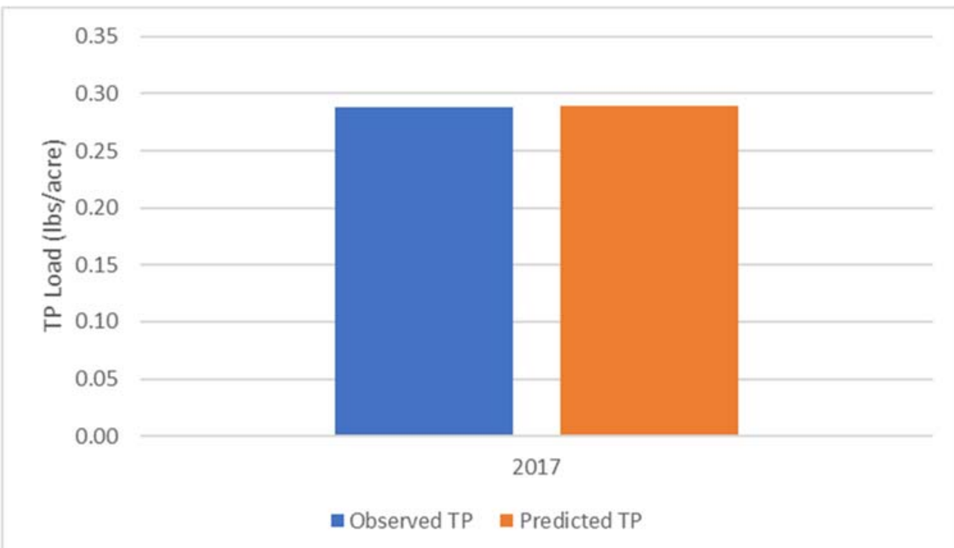

Figure 116. Observed versus model-predicted annual total P at JBT04.

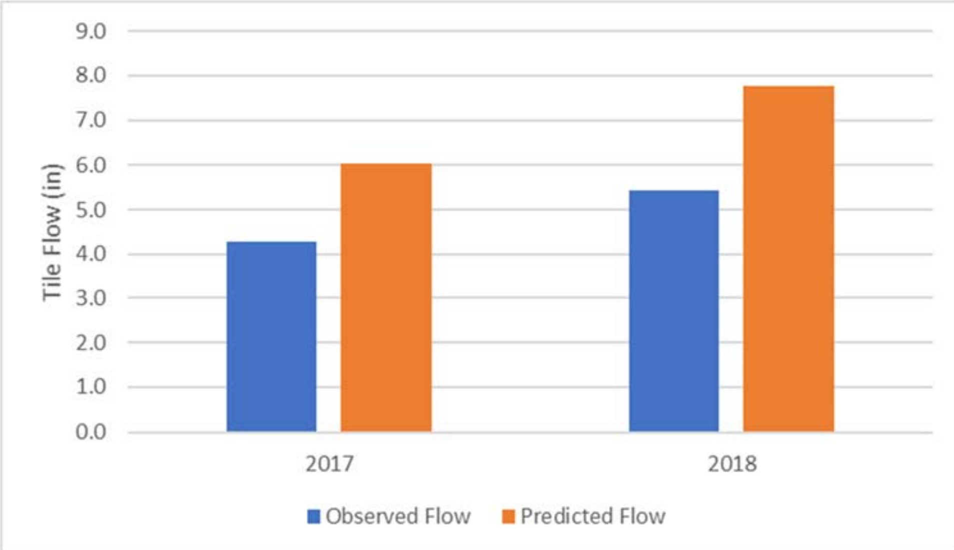

Figure 117. Observed versus model-predicted annual tile flow at JBT05.

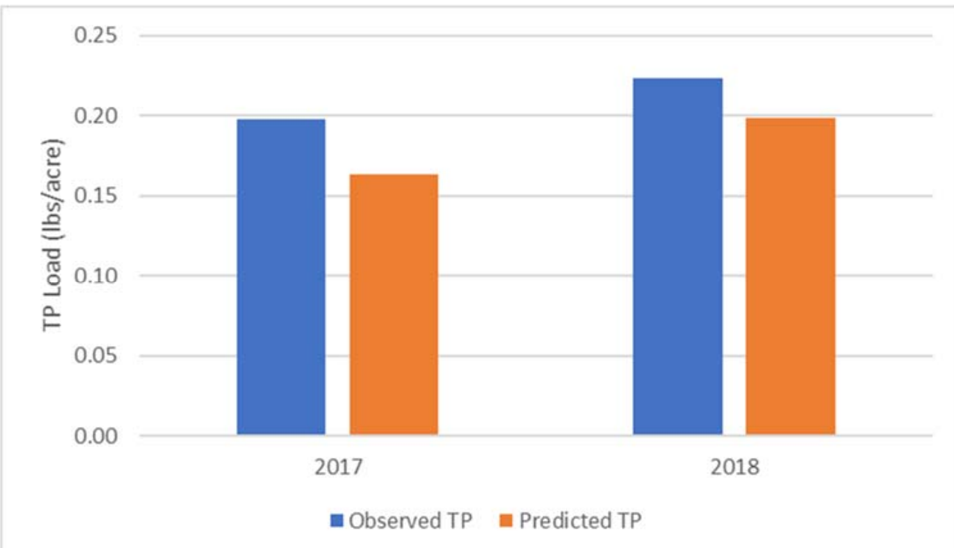

Figure 118. Observed versus model-predicted annual total P at JBT05.

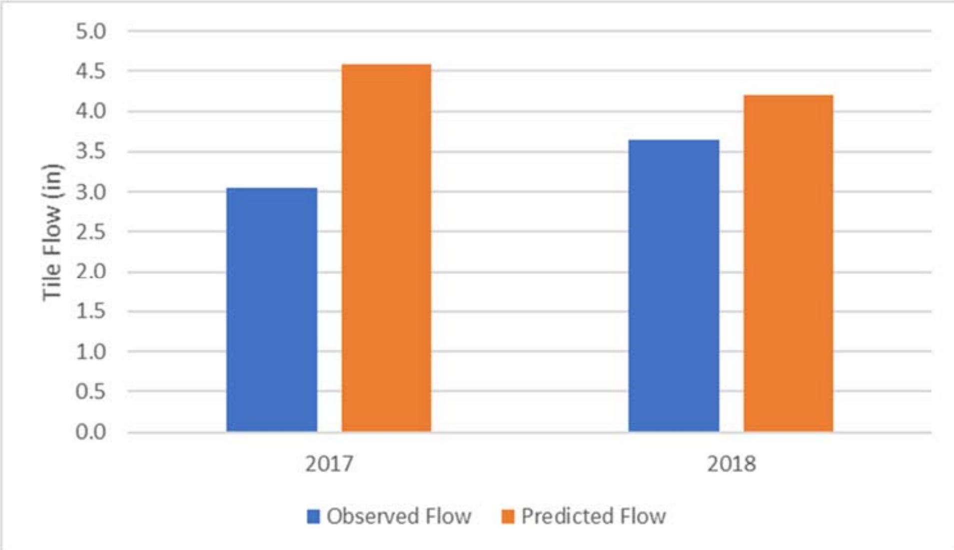

Figure 119. Observed versus model-predicted annual tile flow at JBT07.

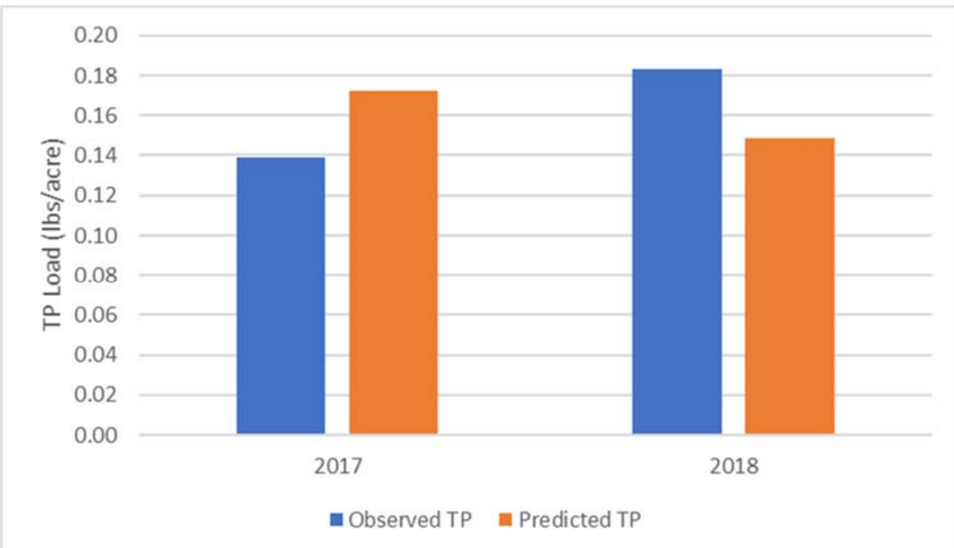

Figure 120. Observed versus model-predicted annual total P at JBT07.

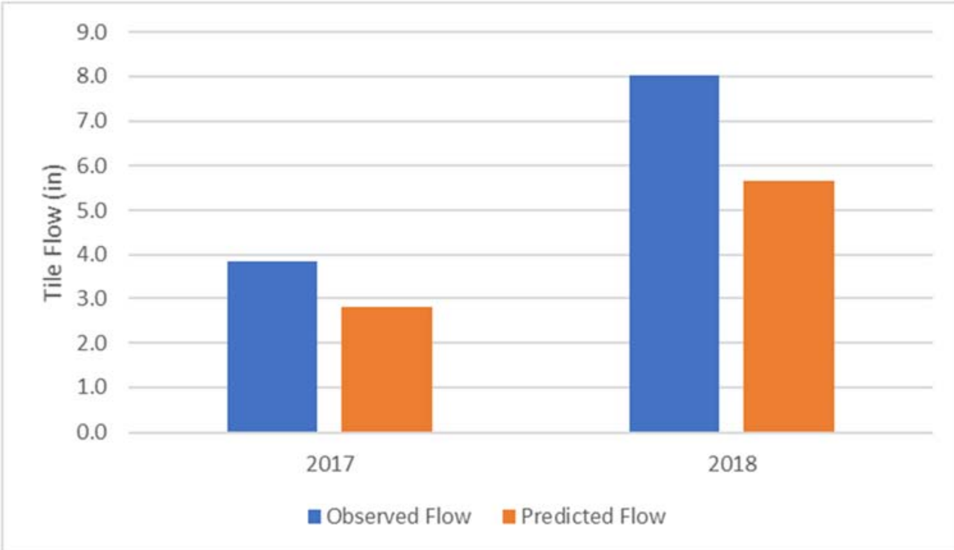

Figure 121. Observed versus model-predicted annual tile flow at JBT11.

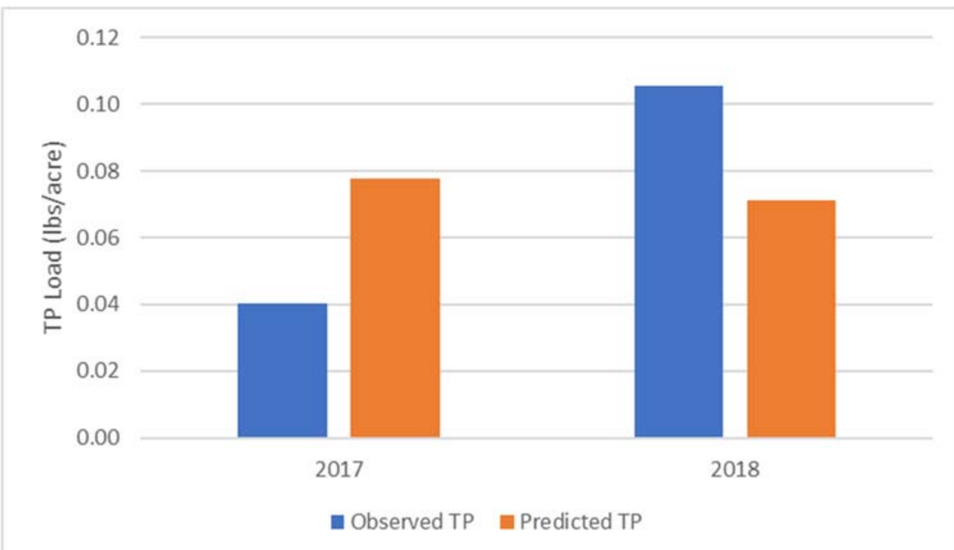

Figure 122. Observed versus model-predicted annual total P at JBT11.

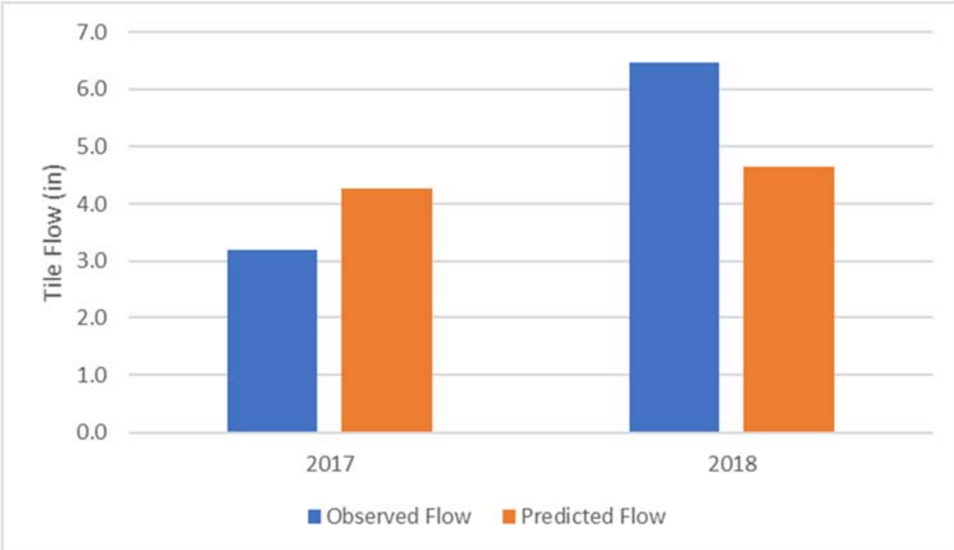

Figure 123. Observed versus model-predicted annual surface runoff (flow) at JBT18.

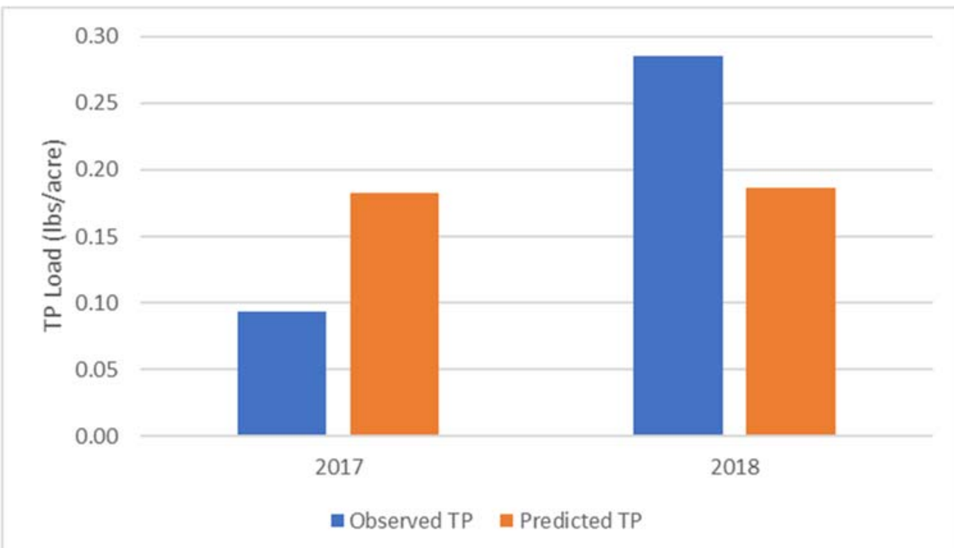

Figure 124. Observed versus model-predicted annual total P at JBT18.

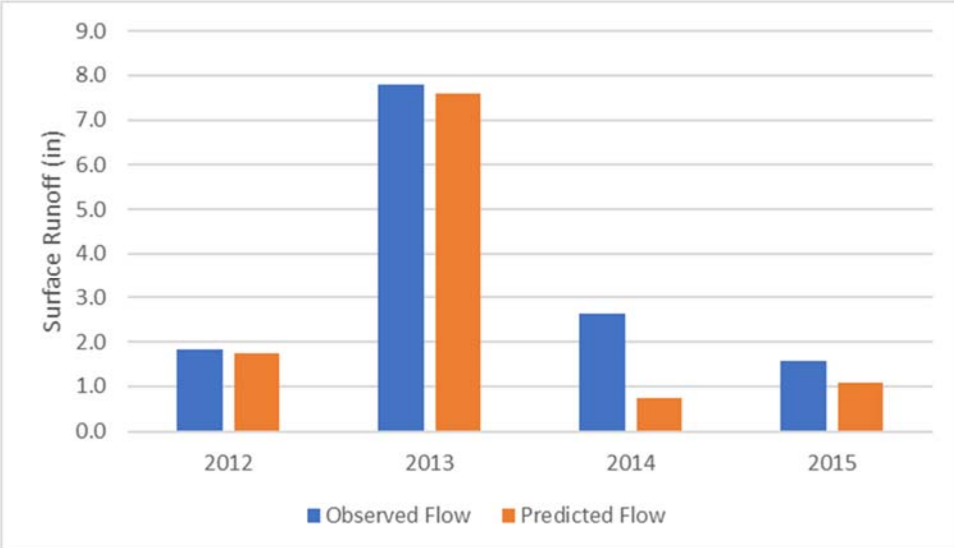

Figure 125. Observed versus model-predicted annual tile flow at PAW1.

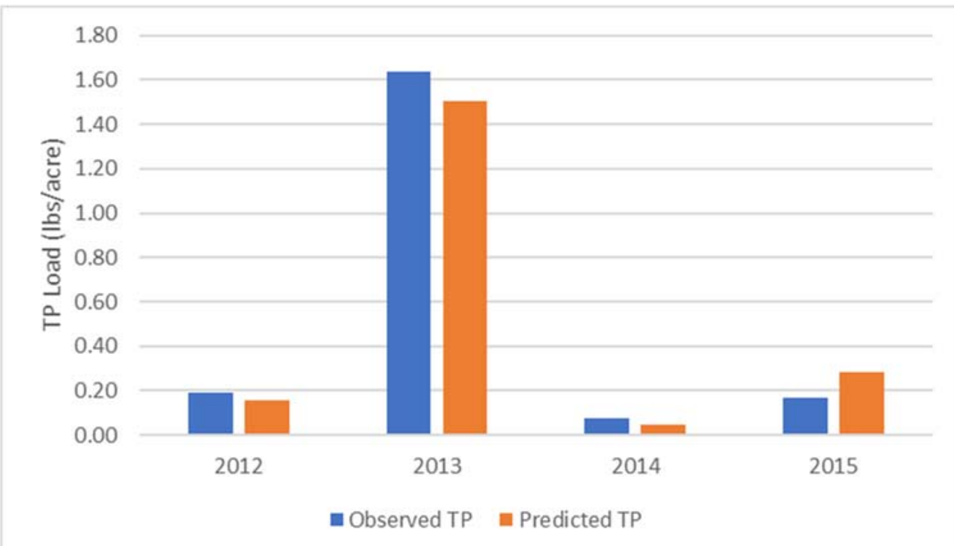

Figure 126. Observed versus model-predicted annual total P at PAW1.

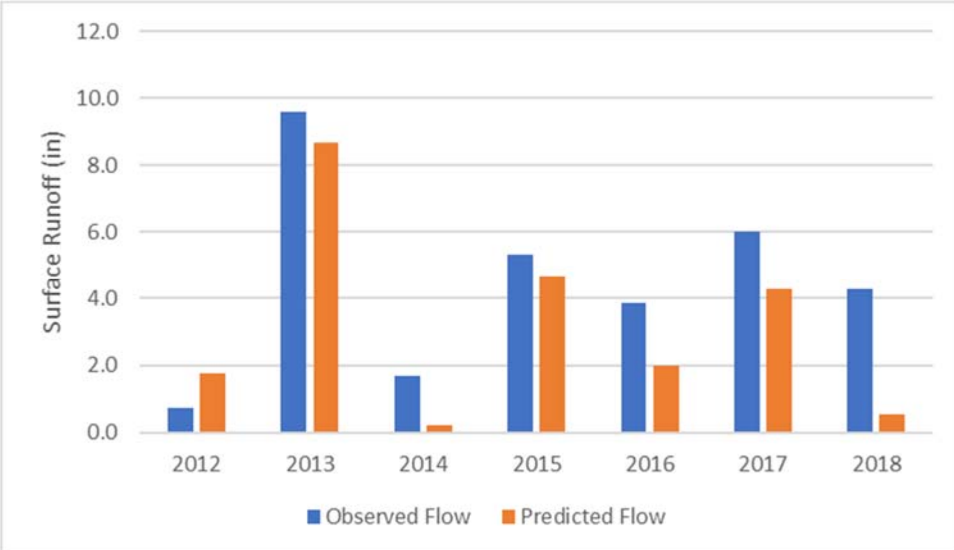

Figure 127. Observed versus model-predicted annual surface runoff (flow) at SHE1.

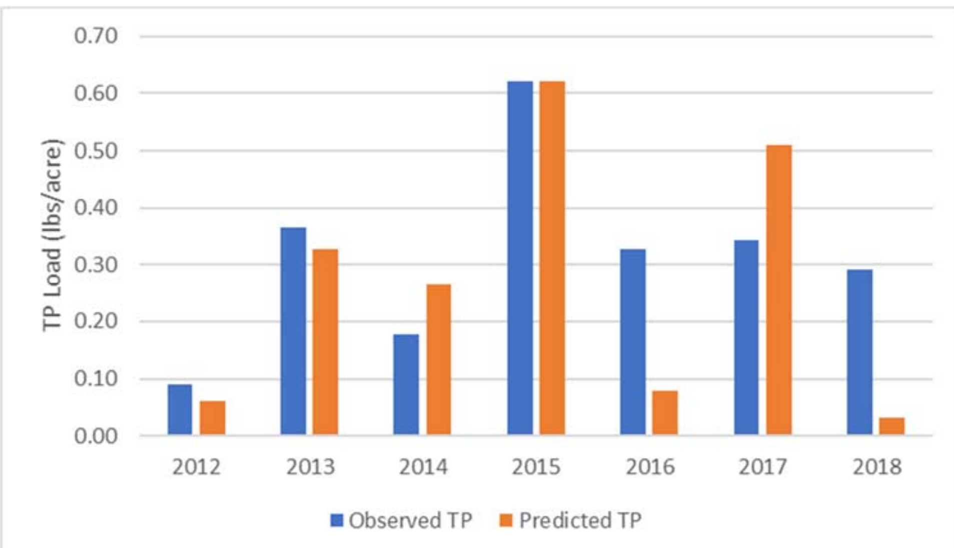

Figure 128. Observed versus model-predicted annual total P at SHE1.

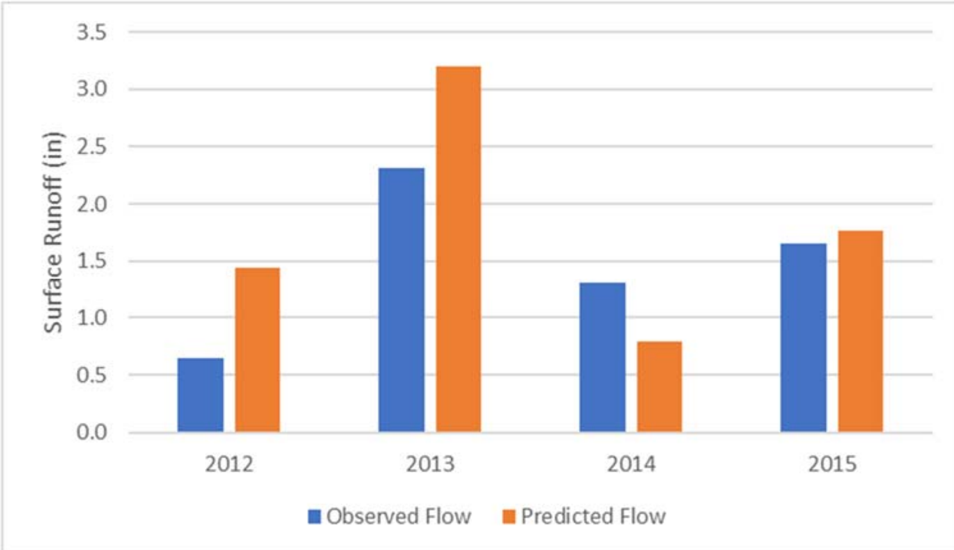

Figure 129. Observed versus model-predicted annual surface runoff (flow) at SHO1.

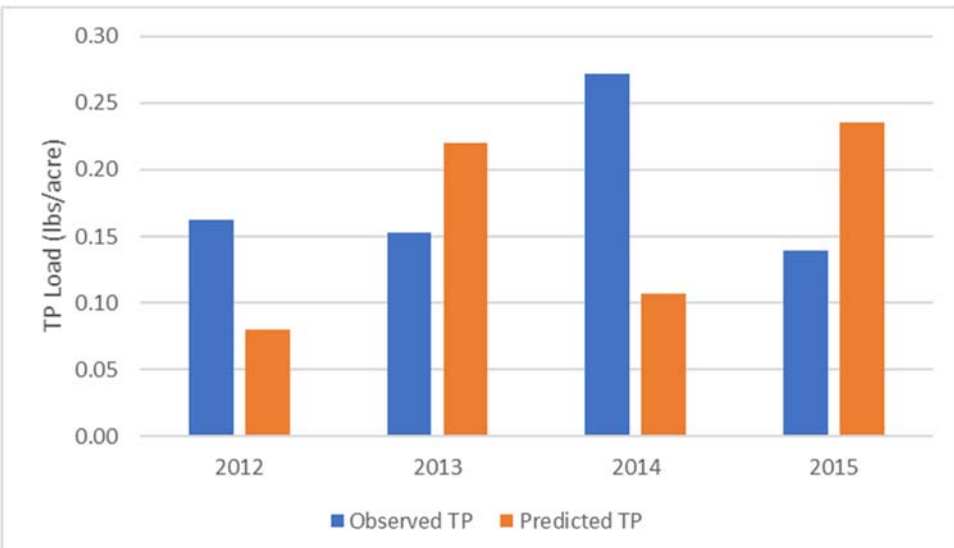

Figure 130. Observed versus model-predicted annual total P at SHO1.

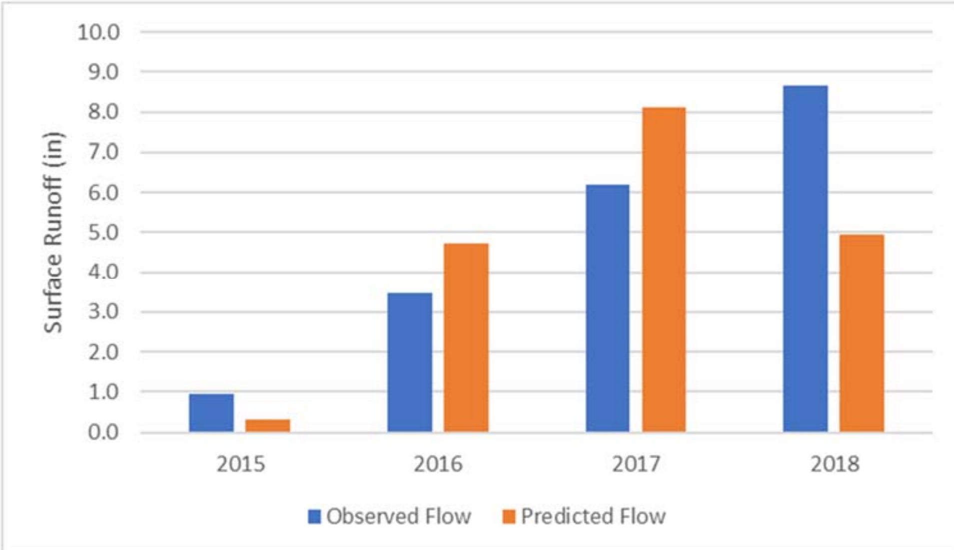

Figure 131. Observed versus model-predicted annual tile flow at M1.

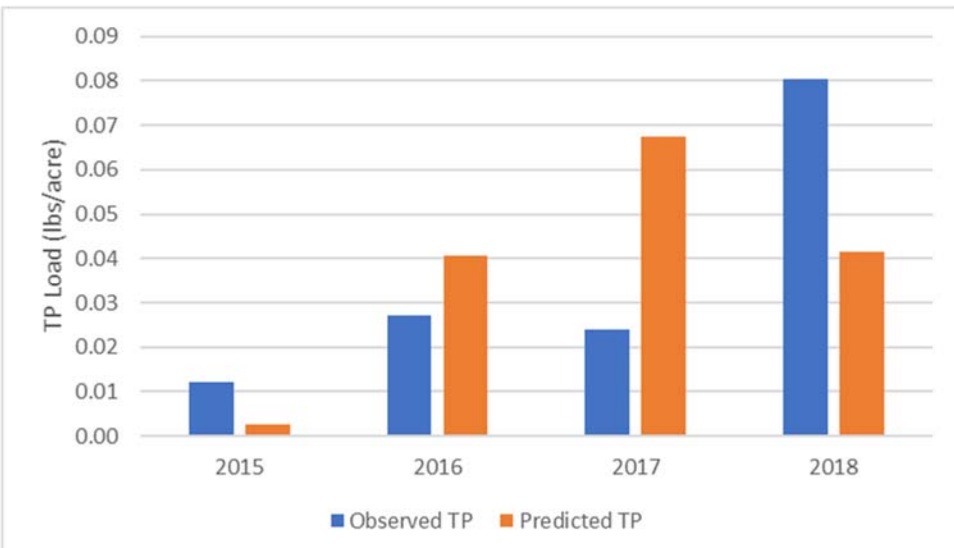

Figure 132. Observed versus model-predicted annual total P in tile drainage at M1.

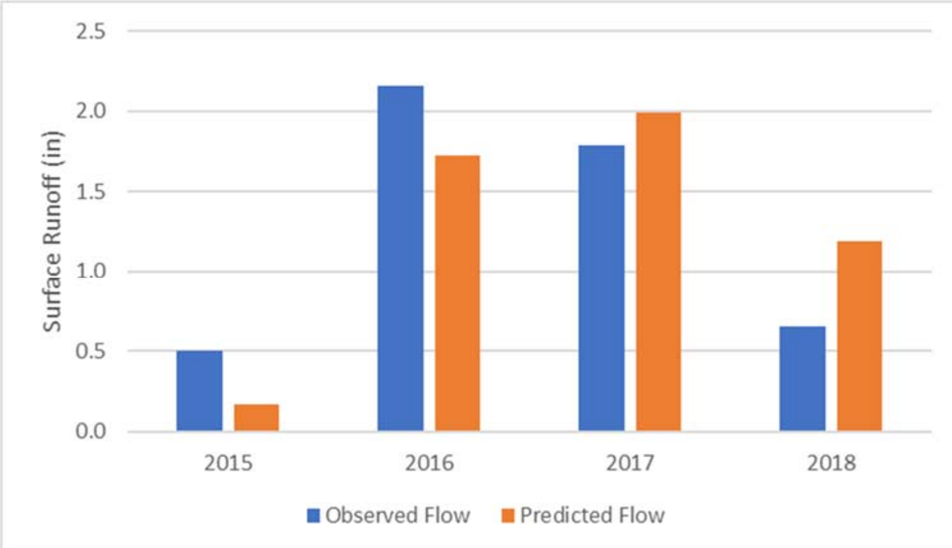

Figure 133. Observed versus model-predicted annual surface runoff (flow) at M1.

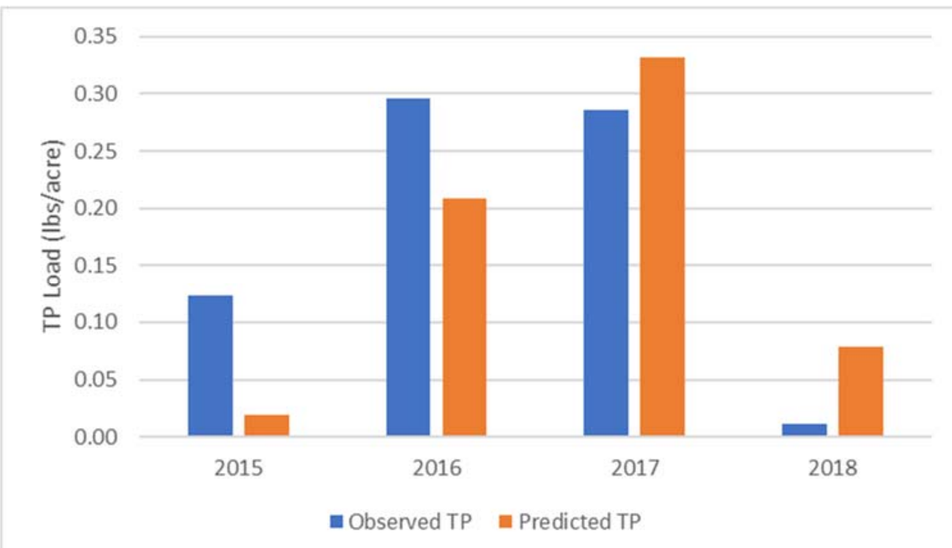

Figure 134. Observed versus model-predicted annual total P in surface runoff at M1.

Appendix F: Tables and Bar Charts Showing Results of Manure Management Scenarios for Optimal P Soils

Table 36. Annual average tile P loads from manure management scenarios, optimal P soils.

Field	Crop/Rotation	Technology	Annual Average Tile P Load (lbs/acre-yr)				
			No Practices	No-till	Cover Crop	Manure Injection	No-till + Cover Crop
JBT01	Corn/soybean	None	0.165	0.157	0.172	0.168	0.159
	Corn/soybean	DAF	0.168	0.153	0.174	X	0.158
	Corn/soybean	Evaporation	0.169	0.154	0.173	X	0.160
JBT11	Continuous hay (alfalfa)	None	0.020	X	X	0.020	X
	Continuous hay (alfalfa)	DAF	0.020	X	X	X	X
	Continuous hay (alfalfa)	Evaporation	0.020	X	X	0.020	X
JBT18	Corn/hay	None	0.120	0.112	0.116	0.121	0.096
	Corn/hay	DAF	0.126	0.118	0.123	X	0.100
	Corn/hay	Evaporation	0.125	0.115	0.121	X	0.098
M1	Continuous corn	None	0.079	0.056	0.075	0.079	0.053
	Continuous corn	DAF	0.079	0.057	0.076	X	0.055
	Continuous corn	Evaporation	0.078	0.055	0.076	X	0.053
PAW1	Continuous corn	None	0.000	0.000	0.000	0.000	0.000
	Continuous corn	DAF	0.000	0.000	0.000	X	0.000
	Continuous corn	Evaporation	0.000	0.000	0.000	X	0.000

Table 37. Annual average surface runoff soluble P loads from manure management scenarios, optimal P soils.

Field	Crop/Rotation	Technology	Annual Average Soluble P Load (lbs/acre-yr)				
			No Practices	No-till	Cover Crop	Manure Injection	No-till + Cover Crop
JBT01	Corn/soybean	None	0.007	0.006	0.004	0.007	0.003
	Corn/soybean	DAF	0.004	0.003	0.003	X	0.002
	Corn/soybean	Evaporation	0.004	0.003	0.003	X	0.002
JBT11	Continuous hay (alfalfa)	None	0.003	X	X	0.003	X
	Continuous hay (alfalfa)	DAF	0.003	X	X	X	X
	Continuous hay (alfalfa)	Evaporation	0.003	X	X	0.003	X
JBT18	Corn/hay	None	0.010	0.008	0.007	0.010	0.005
	Corn/hay	DAF	0.007	0.005	0.006	X	0.004
	Corn/hay	Evaporation	0.007	0.005	0.006	X	0.004
M1	Continuous corn	None	0.009	0.005	0.005	0.009	0.002
	Continuous corn	DAF	0.008	0.003	0.005	X	0.002
	Continuous corn	Evaporation	0.007	0.003	0.004	X	0.002
PAW1	Continuous corn	None	0.075	0.054	0.037	0.075	0.025
	Continuous corn	DAF	0.066	0.036	0.032	X	0.017
	Continuous corn	Evaporation	0.065	0.036	0.032	X	0.017

Table 38. Annual average surface runoff sediment P loads from manure management scenarios, optimal P soils.

Field	Crop/Rotation	Technology	Annual Average Sediment P Load (lbs/acre-yr)				
			No Practices	No-till	Cover Crop	Manure Injection	No-till + Cover Crop
JBT01	Corn/soybean	None	0.351	0.330	0.296	0.351	0.246
	Corn/soybean	DAF	0.292	0.301	0.268	X	0.251
	Corn/soybean	Evaporation	0.293	0.299	0.270	X	0.248
JBT11	Continuous hay (alfalfa)	None	0.033	X	X	0.031	X
	Continuous hay (alfalfa)	DAF	0.036	X	X	X	X
	Continuous hay (alfalfa)	Evaporation	0.034	X	X	0.033	X
JBT18	Corn/hay	None	0.474	0.323	0.437	0.461	0.299
	Corn/hay	DAF	0.414	0.297	0.407	X	0.291
	Corn/hay	Evaporation	0.414	0.293	0.405	X	0.287
M1	Continuous corn	None	0.537	0.420	0.416	0.532	0.293
	Continuous corn	DAF	0.461	0.383	0.382	X	0.307
	Continuous corn	Evaporation	0.462	0.387	0.382	X	0.297
PAW1	Continuous corn	None	3.390	2.943	3.143	3.361	2.235
	Continuous corn	DAF	3.186	2.736	2.985	X	2.195
	Continuous corn	Evaporation	3.194	2.728	2.992	X	2.191

Table 39. Annual average total P loads from manure management scenarios, optimal P soils.

Field	Crop/Rotation	Technology	Annual Average Total P Load (lbs/acre-yr)				
			No Practices	No-till	Cover Crop	Manure Injection	No-till + Cover Crop
JBT01	Corn/soybean	None	0.523	0.493	0.471	0.526	0.408
	Corn/soybean	DAF	0.465	0.457	0.445	X	0.412
	Corn/soybean	Evaporation	0.466	0.456	0.446	X	0.411
JBT11	Continuous hay (alfalfa)	None	0.056	X	X	0.054	X
	Continuous hay (alfalfa)	DAF	0.059	X	X	X	X
	Continuous hay (alfalfa)	Evaporation	0.057	X	X	0.056	X
JBT18	Corn/hay	None	0.604	0.443	0.560	0.591	0.400
	Corn/hay	DAF	0.547	0.421	0.536	X	0.395
	Corn/hay	Evaporation	0.546	0.413	0.532	X	0.388
M1	Continuous corn	None	0.625	0.481	0.497	0.619	0.349
	Continuous corn	DAF	0.547	0.443	0.462	X	0.364
	Continuous corn	Evaporation	0.548	0.445	0.463	X	0.352
PAW1	Continuous corn	None	3.464	2.997	3.179	3.436	2.261
	Continuous corn	DAF	3.251	2.772	3.017	X	2.212
	Continuous corn	Evaporation	3.259	2.764	3.023	X	2.208

Table 40. Annual average mineral P applied to field in manure management scenarios, optimal P soils.

Field	Crop/Rotation	Technology	Annual Average Total P Applied (lbs/acre-yr)				
			No Practices	No-till	Cover Crop	Manure Injection	No-till + Cover Crop
JBT01	Corn/soybean	None	8.815	8.815	8.815	8.815	8.815
	Corn/soybean	DAF	8.726	8.726	8.726	X	8.726
	Corn/soybean	Evaporation	8.743	8.743	8.743	X	8.743
JBT11	Continuous hay (alfalfa)	None	8.855	X	X	8.855	X
	Continuous hay (alfalfa)	DAF	8.726	X	X	X	X
	Continuous hay (alfalfa)	Evaporation	8.743	X	X	8.743	X
JBT18	Corn/hay	None	8.815	8.815	8.815	8.815	8.815
	Corn/hay	DAF	8.726	8.726	8.726	X	8.726
	Corn/hay	Evaporation	8.743	8.743	8.743	X	8.743
M1	Continuous corn	None	8.815	8.815	8.815	8.815	8.815
	Continuous corn	DAF	8.726	8.726	8.726	X	8.726
	Continuous corn	Evaporation	8.743	8.743	8.743	X	8.743
PAW1	Continuous corn	None	8.815	8.815	8.815	8.815	8.815
	Continuous corn	DAF	8.726	8.726	8.726	X	8.726
	Continuous corn	Evaporation	8.743	8.743	8.743	X	8.743

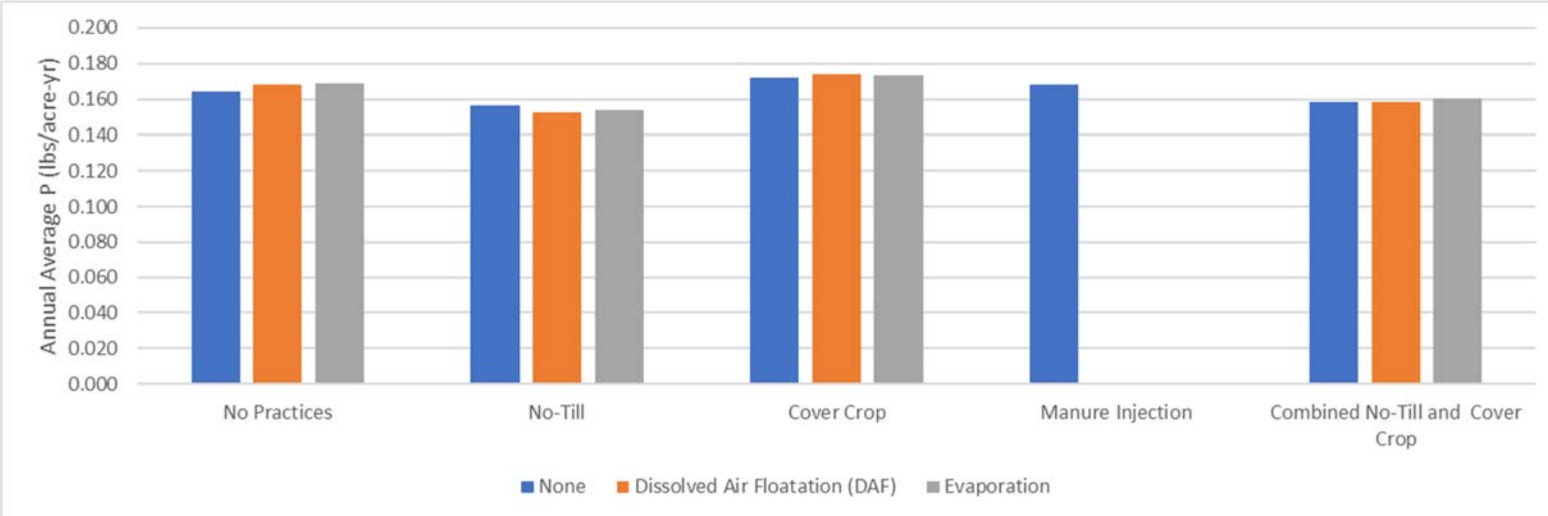

Figure 135. Annual average tile P loads for JBT01 with optimal P soils, based on combinations of manure management technology and conservation practices.

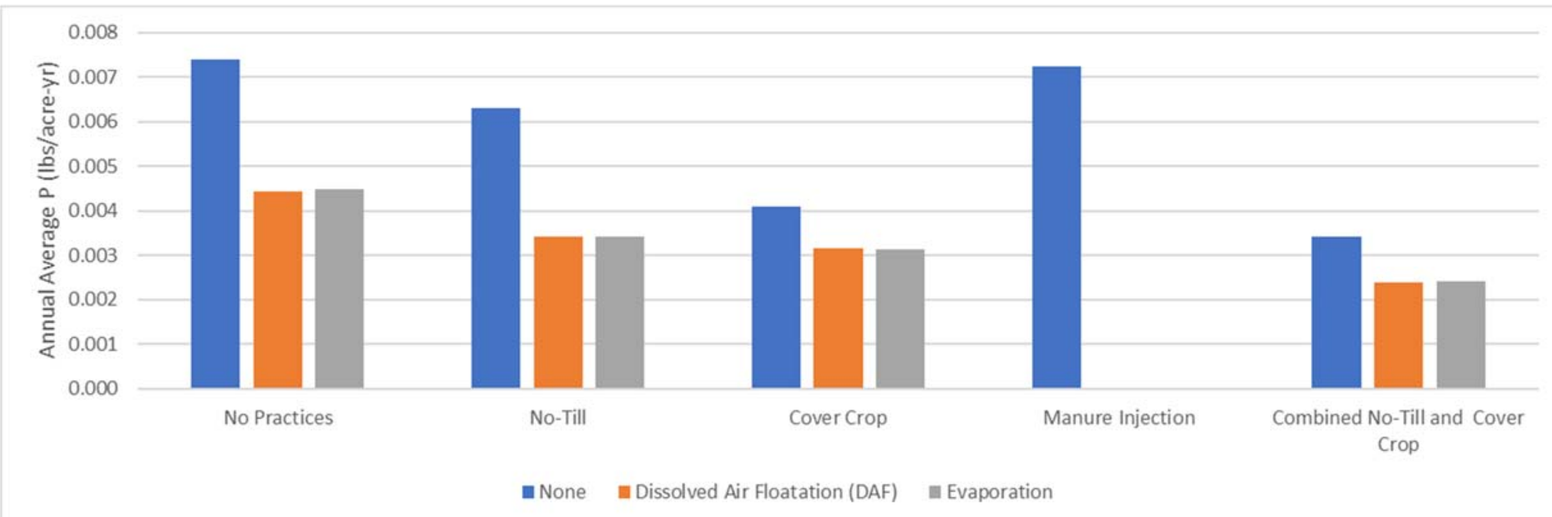

Figure 136. Annual average surface runoff soluble P loads for JBT01 with optimal P soils, based on combinations of manure management technology and conservation practices.

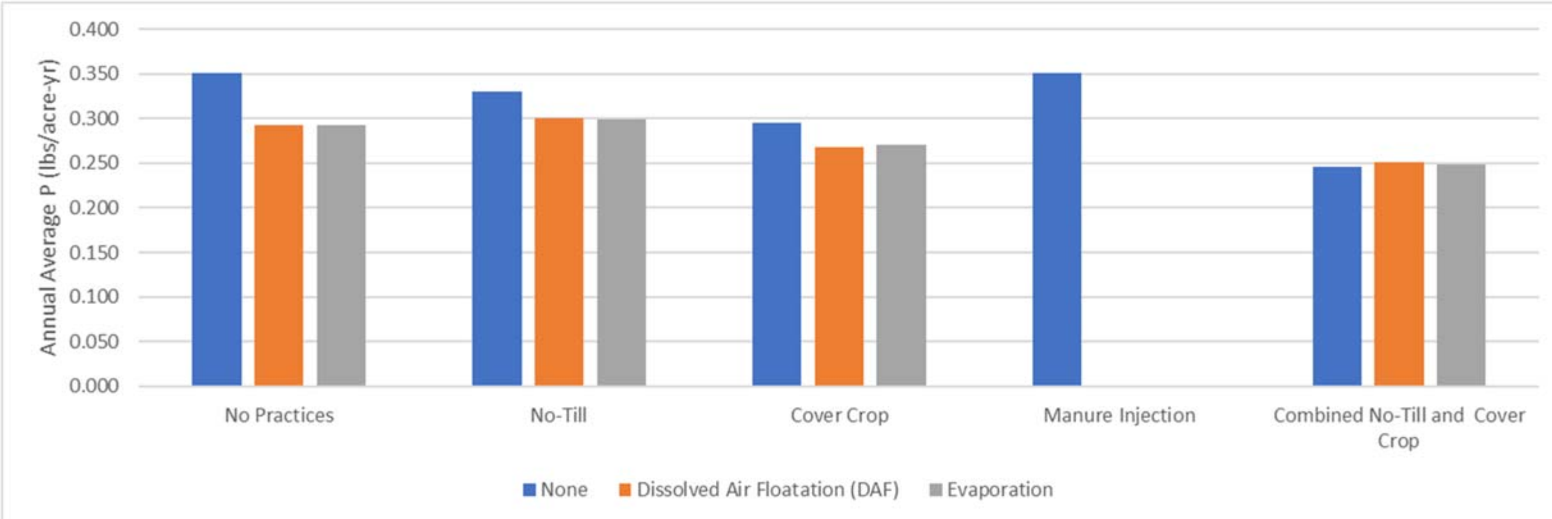

Figure 137. Annual average surface runoff sediment P loads for JBT01 with optimal P soils, based on combinations of manure management technology and conservation practices.

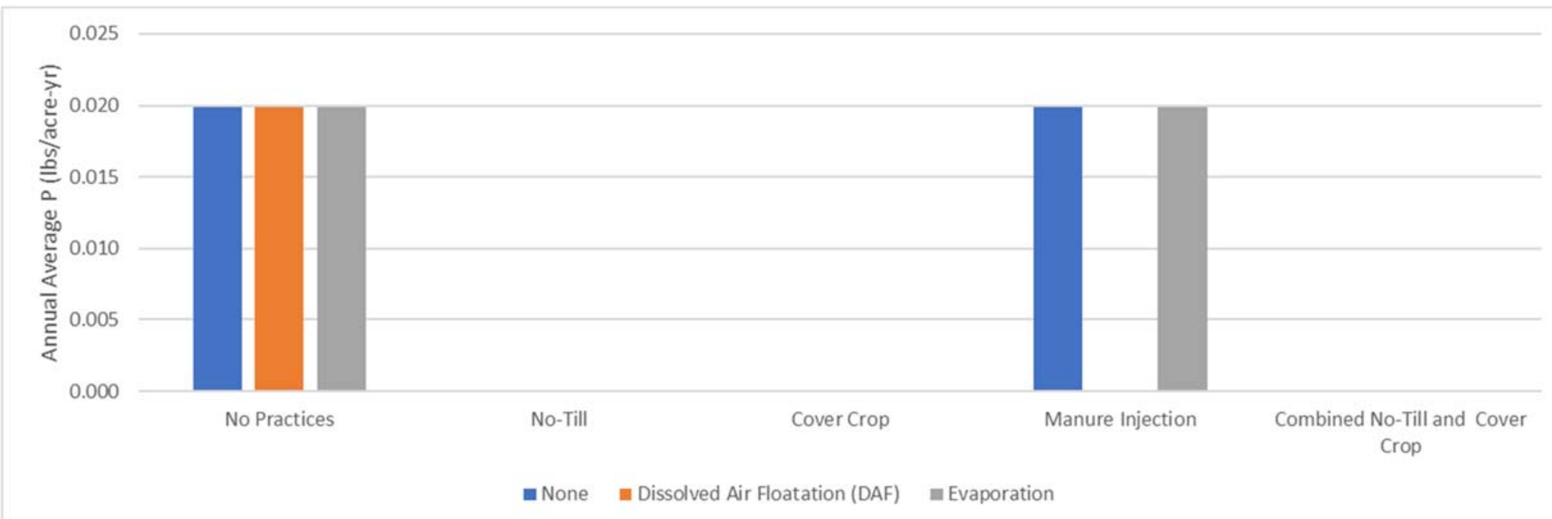

Figure 138. Annual average tile P loads for JBT11 with optimal soils, based on combinations of manure management technology and conservation practices. No-till, cover crop, and combined no-till and cover crop options were not simulated for JBT11 (permanent hay).

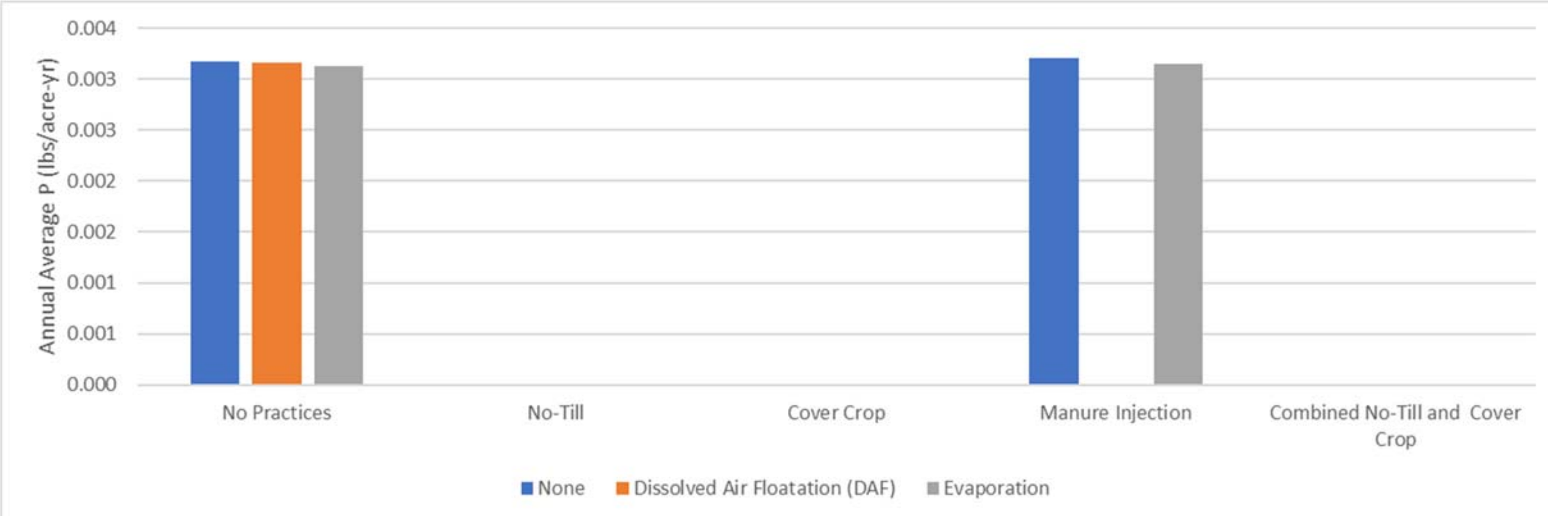

Figure 139. Annual average surface runoff soluble P loads for JBT11 with optimal P soils, based on combinations of manure management technology and conservation practices. No-till, cover crop, and combined no-till and cover crop options were not simulated for JBT11 (permanent hay).

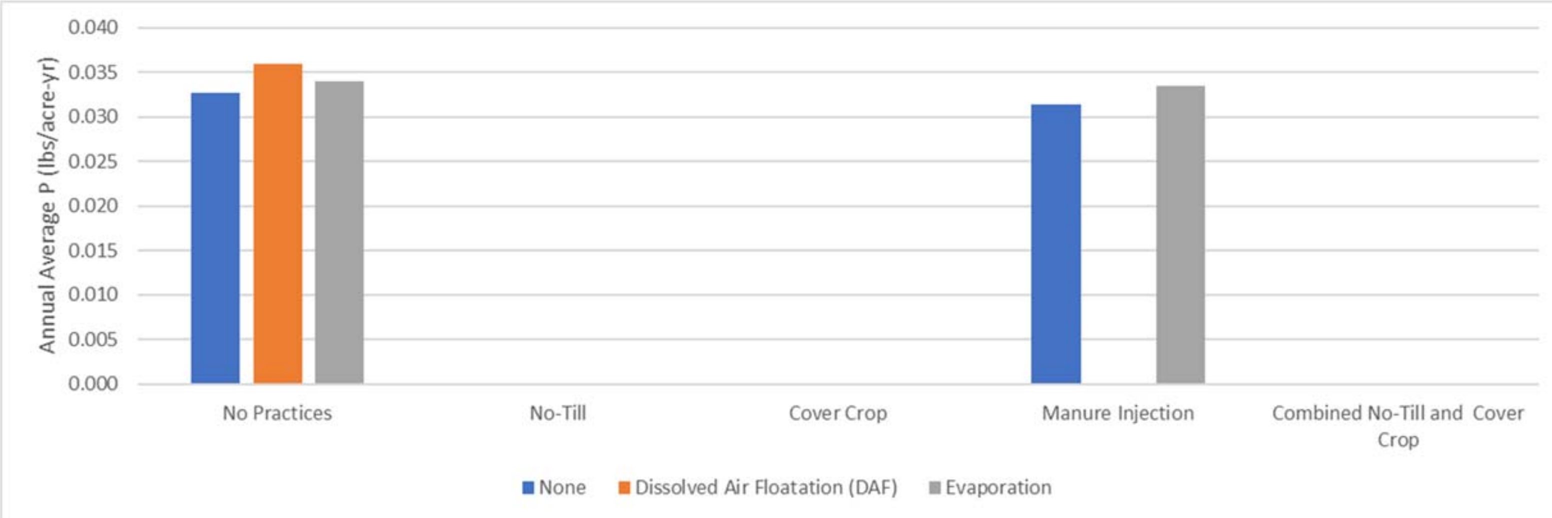

Figure 140. Annual average surface runoff sediment P loads for JBT11 with optimal P soils, based on combinations of manure management technology and conservation practices. No-till, cover crop, and combined no-till and cover crop options were not simulated for JBT11 (permanent hay).

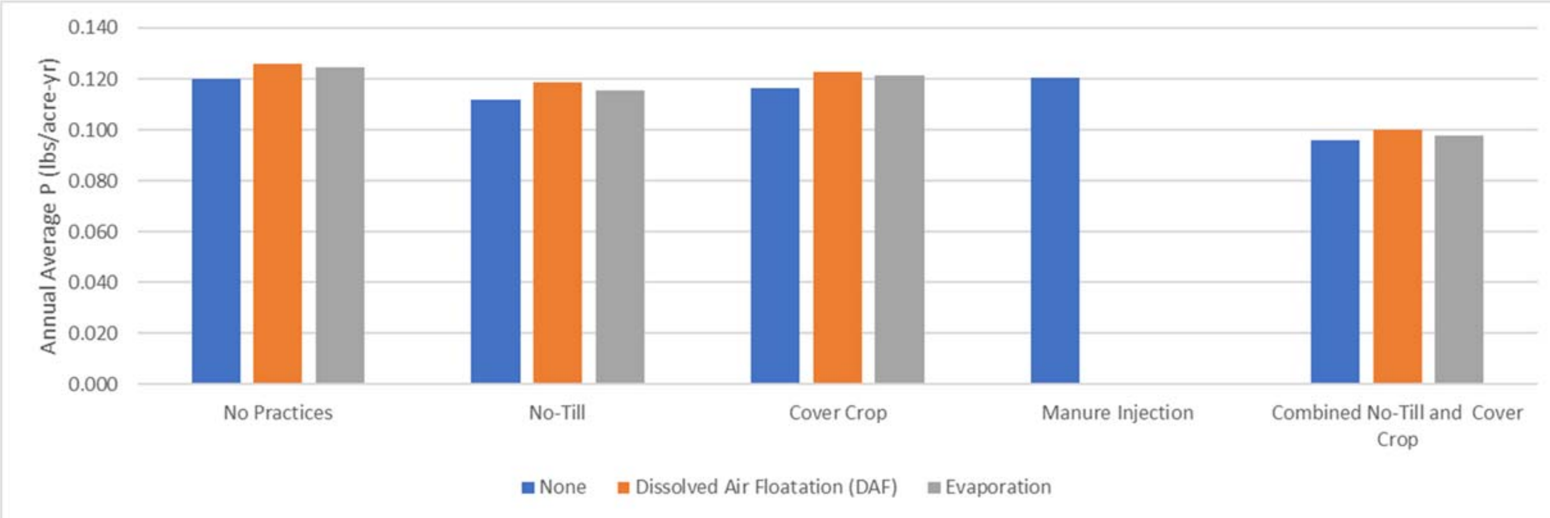

Figure 141. Annual average tile P loads for JBT18 with optimal P soils, based on combinations of manure management technology and conservation practices.

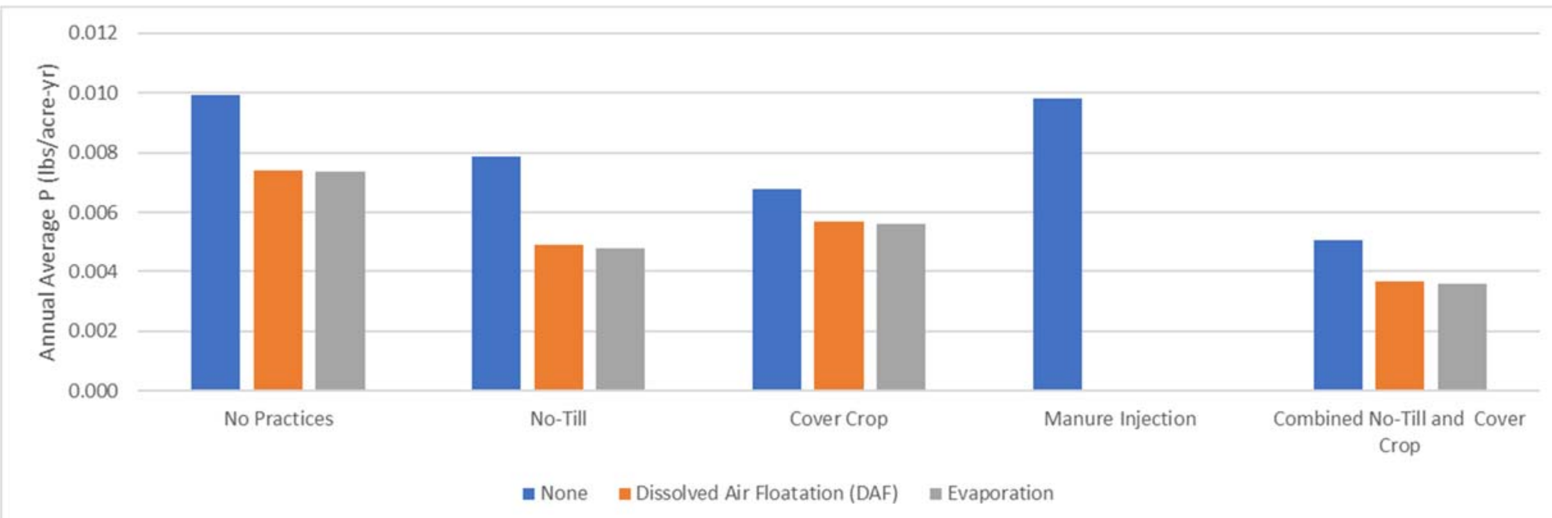

Figure 142. Annual average surface runoff soluble P loads for JBT18 with optimal P soils, based on combinations of manure management technology and conservation practices.

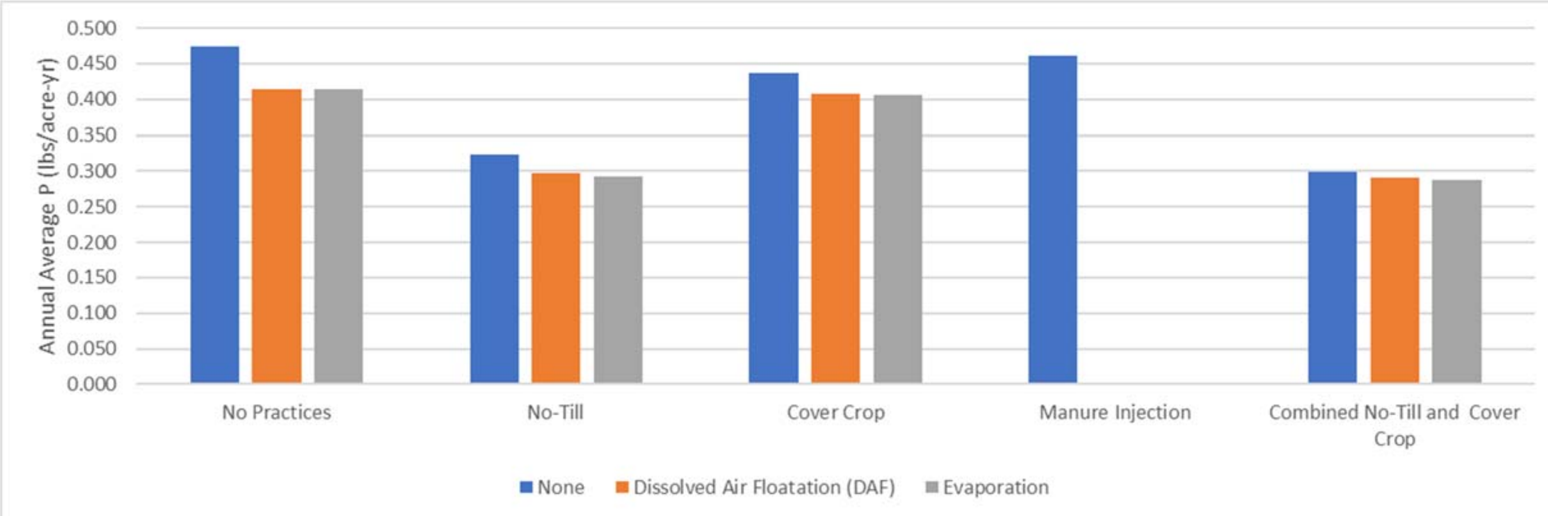

Figure 143. Annual average surface runoff sediment P loads for JBT18 with optimal P soils, based on combinations of manure management technology and conservation practices.

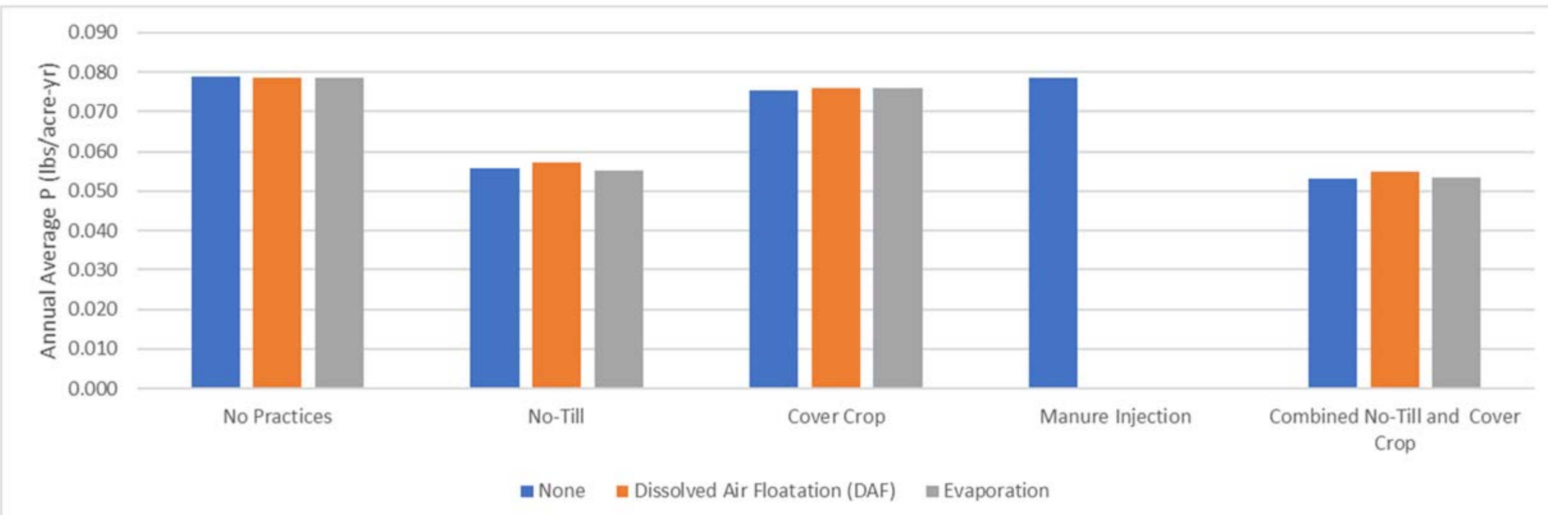

Figure 144. Annual average tile P loads for M1 with optimal P soils, based on combinations of manure management technology and conservation practices.

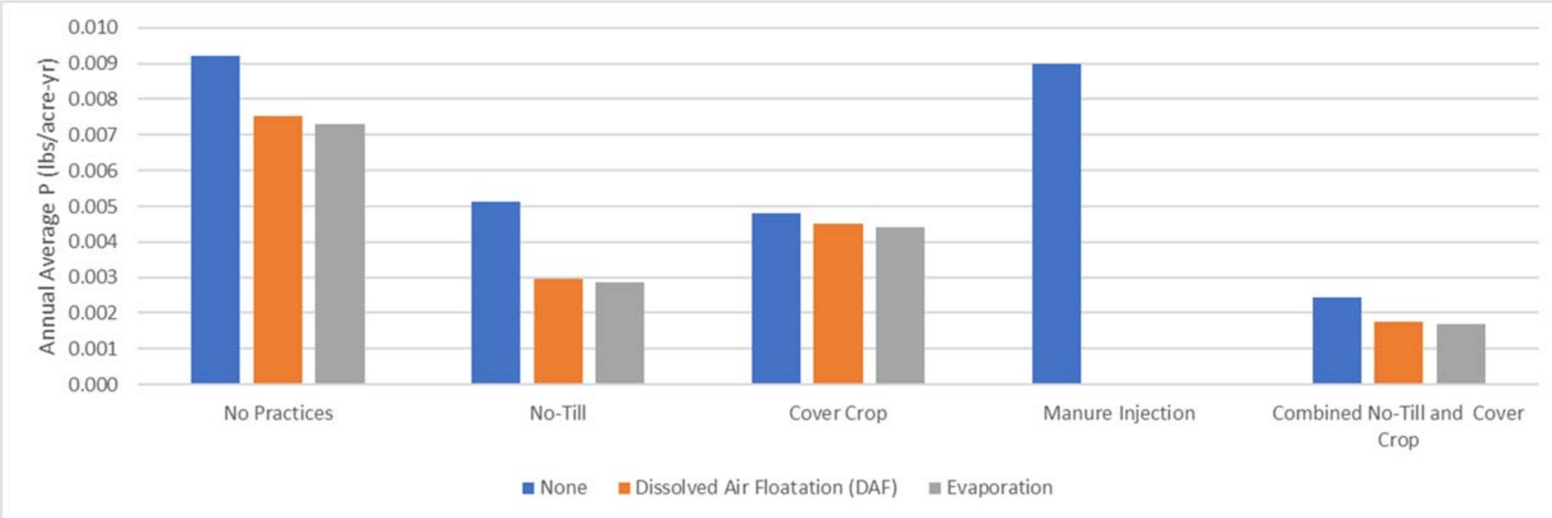

Figure 145. Average annual surface runoff soluble P loads for M1 with optimal P soils, based on combinations of manure management technology and conservation practices.

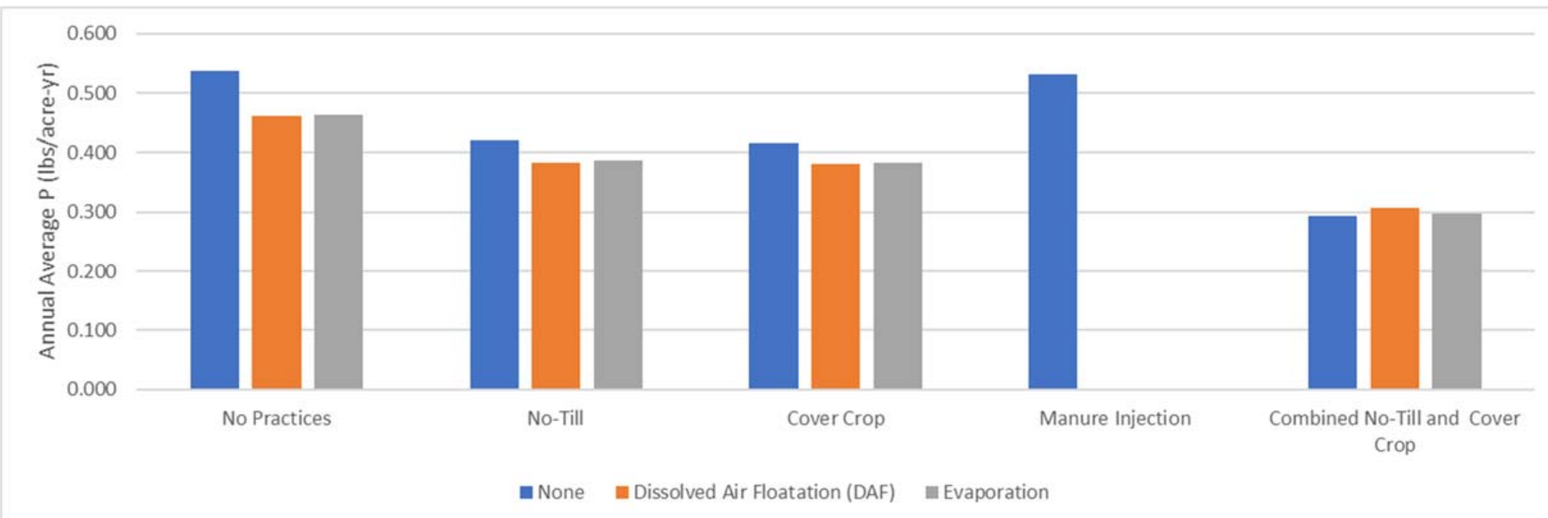

Figure 146. Annual average surface runoff sediment P loads for M1 with optimal P soils, based on combinations of manure management technology and conservation practices.

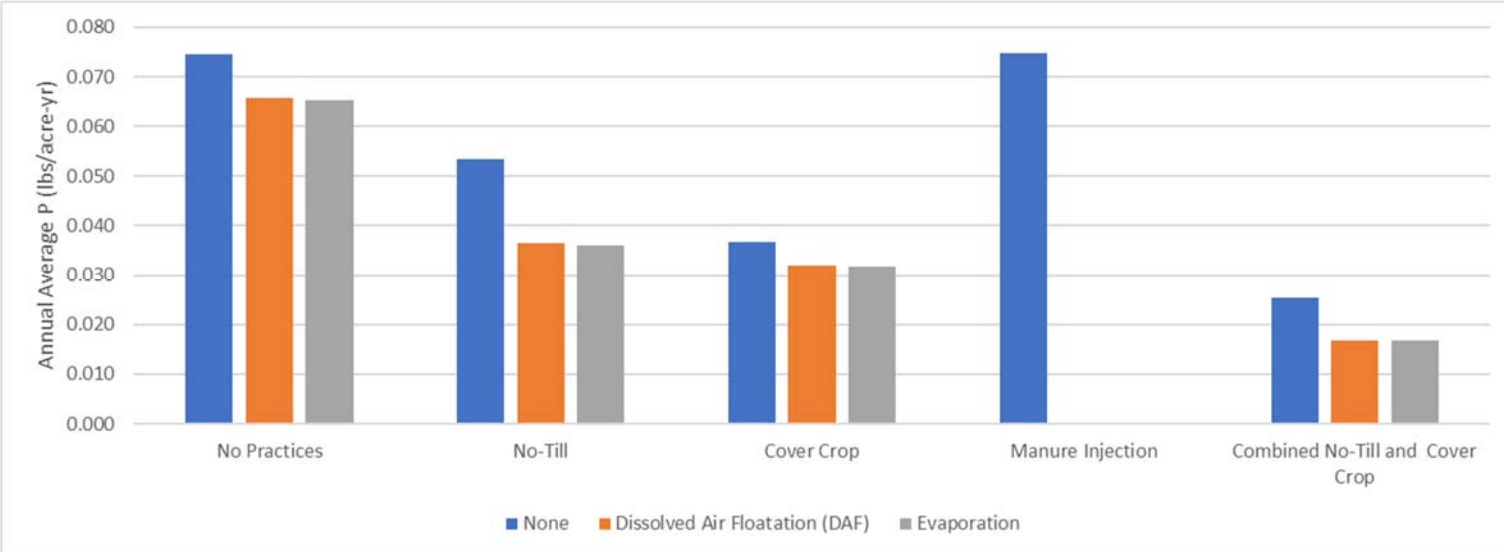

Figure 147. Average annual surface runoff soluble P loads for PAW1 with optimal P soils, based on combinations of manure management technology and conservation practices.

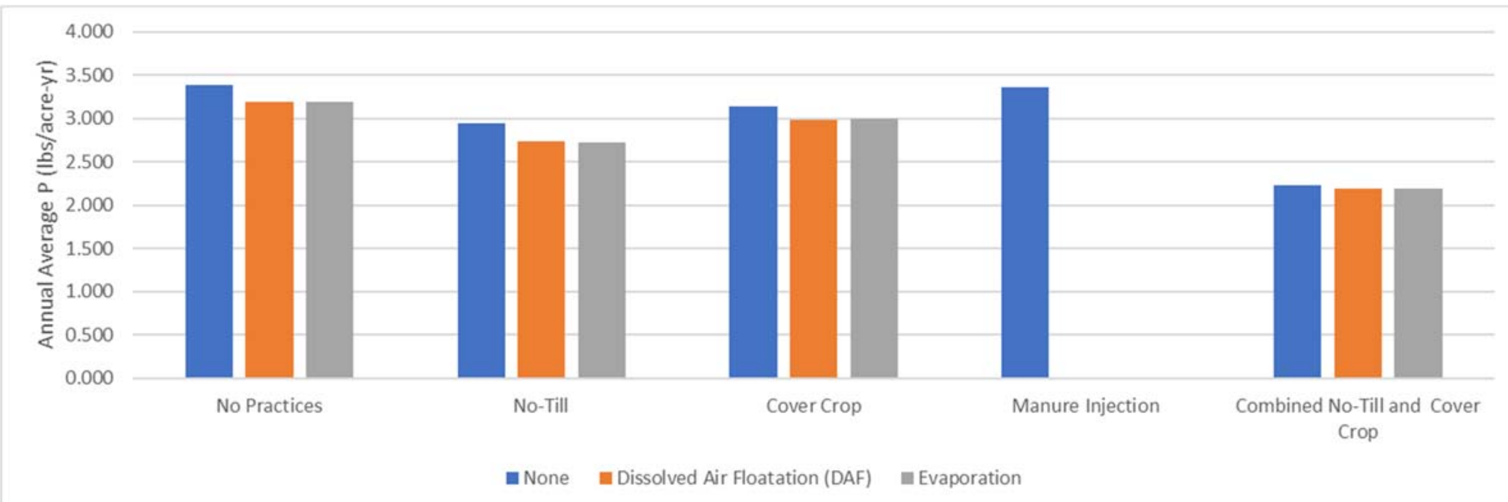

Figure 148. Annual average surface runoff sediment P loads for PAW1 with optimal P soils, based on combinations of manure management technology and conservation practices.

Appendix G: Tables and Bar Charts Showing Results of Manure Management Scenarios for High P Soils

Table 41. Annual average tile P loads from manure management scenarios, high P soils.

Field	Crop/Rotation	Technology	Annual Average Tile P Load (lbs/acre-yr)				
			No Practices	No-till	Cover Crop	Manure Injection	No-till + Cover Crop
JBT01	Corn/soybean	None	0.357	0.335	0.367	0.359	0.339
	Corn/soybean	DAF	0.272	0.251	0.292	X	0.262
	Corn/soybean	Evaporation	0.252	0.275	0.259	X	0.278
JBT11	Continuous hay (alfalfa)	None	0.026	X	X	0.026	X
	Continuous hay (alfalfa)	DAF	0.025	X	X	X	X
	Continuous hay (alfalfa)	Evaporation	0.025	X	X	0.025	X
JBT18	Corn/hay	None	0.272	0.271	0.268	0.273	0.250
	Corn/hay	DAF	0.221	0.212	0.218	X	0.209
	Corn/hay	Evaporation	0.215	0.203	0.216	X	0.201
M1	Continuous corn	None	0.151	0.137	0.147	0.151	0.134
	Continuous corn	DAF	0.117	0.099	0.116	X	0.097
	Continuous corn	Evaporation	0.115	0.094	0.115	X	0.093
PAW1	Continuous corn	None	0.000	0.000	0.000	0.000	0.000
	Continuous corn	DAF	0.000	0.000	0.000	X	0.000
	Continuous corn	Evaporation	0.000	0.000	0.000	X	0.000

Table 42. Annual average surface runoff soluble P loads from manure management scenarios, high P soils.

Field	Crop/Rotation	Technology	Annual Average Soluble P Load (lbs/acre-yr)				
			No Practices	No-till	Cover Crop	Manure Injection	No-till + Cover Crop
JBT01	Corn/soybean	None	0.017	0.014	0.010	0.016	0.008
	Corn/soybean	DAF	0.006	0.005	0.004	X	0.004
	Corn/soybean	Evaporation	0.006	0.005	0.004	X	0.004
JBT11	Continuous hay (alfalfa)	None	0.018	X	X	0.019	X
	Continuous hay (alfalfa)	DAF	0.003	X	X	X	X
	Continuous hay (alfalfa)	Evaporation	0.003	X	X	0.003	X
JBT18	Corn/hay	None	0.028	0.020	0.021	0.028	0.014
	Corn/hay	DAF	0.009	0.006	0.007	X	0.005
	Corn/hay	Evaporation	0.009	0.006	0.007	X	0.005
M1	Continuous corn	None	0.025	0.011	0.014	0.025	0.006
	Continuous corn	DAF	0.007	0.004	0.005	X	0.003
	Continuous corn	Evaporation	0.007	0.003	0.005	X	0.002
PAW1	Continuous corn	None	0.237	0.090	0.111	0.235	0.053
	Continuous corn	DAF	0.086	0.056	0.050	X	0.033
	Continuous corn	Evaporation	0.090	0.051	0.050	X	0.032

Table 43. Annual average surface runoff sediment P loads from manure management scenarios, high P soils.

Field	Crop/Rotation	Technology	Annual Average Sediment P Load (lbs/acre-yr)				
			No Practices	No-till	Cover Crop	Manure Injection	No-till + Cover Crop
JBT01	Corn/soybean	None	0.429	0.402	0.351	0.428	0.292
	Corn/soybean	DAF	0.371	0.372	0.349	X	0.309
	Corn/soybean	Evaporation	0.365	0.377	0.332	X	0.312
JBT11	Continuous hay (alfalfa)	None	0.024	X	X	0.022	X
	Continuous hay (alfalfa)	DAF	0.019	X	X	X	X
	Continuous hay (alfalfa)	Evaporation	0.024	X	X	0.023	X
JBT18	Corn/hay	None	0.558	0.371	0.503	0.545	0.334
	Corn/hay	DAF	0.454	0.301	0.447	X	0.306
	Corn/hay	Evaporation	0.450	0.290	0.444	X	0.297
M1	Continuous corn	None	0.594	0.481	0.454	0.589	0.321
	Continuous corn	DAF	0.491	0.406	0.407	X	0.333
	Continuous corn	Evaporation	0.491	0.399	0.407	X	0.312
PAW1	Continuous corn	None	3.884	3.379	3.581	3.833	2.567
	Continuous corn	DAF	3.495	3.281	3.257	X	2.626
	Continuous corn	Evaporation	3.586	3.408	3.365	X	2.749

Table 44. Annual average total P loads from manure management scenarios, high P soils.

Field	Crop/Rotation	Technology	Annual Average Total P Load (lbs/acre-yr)				
			No Practices	No-till	Cover Crop	Manure Injection	No-till + Cover Crop
JBT01	Corn/soybean	None	0.803	0.751	0.728	0.802	0.640
	Corn/soybean	DAF	0.649	0.628	0.645	X	0.574
	Corn/soybean	Evaporation	0.622	0.657	0.595	X	0.594
JBT11	Continuous hay (alfalfa)	None	0.068	X	X	0.066	X
	Continuous hay (alfalfa)	DAF	0.047	X	X	X	X
	Continuous hay (alfalfa)	Evaporation	0.052	X	X	0.051	X
JBT18	Corn/hay	None	0.858	0.662	0.792	0.845	0.598
	Corn/hay	DAF	0.684	0.519	0.671	X	0.520
	Corn/hay	Evaporation	0.673	0.499	0.667	X	0.502
M1	Continuous corn	None	0.770	0.629	0.616	0.765	0.461
	Continuous corn	DAF	0.615	0.508	0.529	X	0.433
	Continuous corn	Evaporation	0.613	0.496	0.527	X	0.408
PAW1	Continuous corn	None	4.121	3.469	3.692	4.067	2.620
	Continuous corn	DAF	3.581	3.337	3.307	X	2.659
	Continuous corn	Evaporation	3.676	3.458	3.416	X	2.781

Table 45. Annual average mineral P applied to field in manure management scenarios, high P soils.

Field	Crop/Rotation	Technology	Annual Average Total P Applied (lbs/acre-yr)				
			No Practices	No-till	Cover Crop	Manure Injection	No-till + Cover Crop
JBT01	Corn/soybean	None	17.638	17.638	17.638	17.638	17.638
	Corn/soybean	DAF	12.549	15.039	14.088	X	15.014
	Corn/soybean	Evaporation	11.129	15.846	10.652	X	15.595
JBT11	Continuous hay (alfalfa)	None	17.639	X	X	17.638	X
	Continuous hay (alfalfa)	DAF	0.823	X	X	X	X
	Continuous hay (alfalfa)	Evaporation	1.902	X	X	1.903	X
JBT18	Corn/hay	None	17.638	17.638	17.638	17.638	17.638
	Corn/hay	DAF	11.847	9.512	11.159	X	14.777
	Corn/hay	Evaporation	10.195	9.626	10.972	X	14.195
M1	Continuous corn	None	17.638	17.638	17.638	17.638	17.638
	Continuous corn	DAF	7.077	10.183	8.445	X	11.457
	Continuous corn	Evaporation	5.691	7.504	6.452	X	8.310
PAW1	Continuous corn	None	17.638	17.638	17.638	17.638	17.638
	Continuous corn	DAF	13.111	19.607	13.207	X	21.681
	Continuous corn	Evaporation	13.694	21.602	14.199	X	22.362

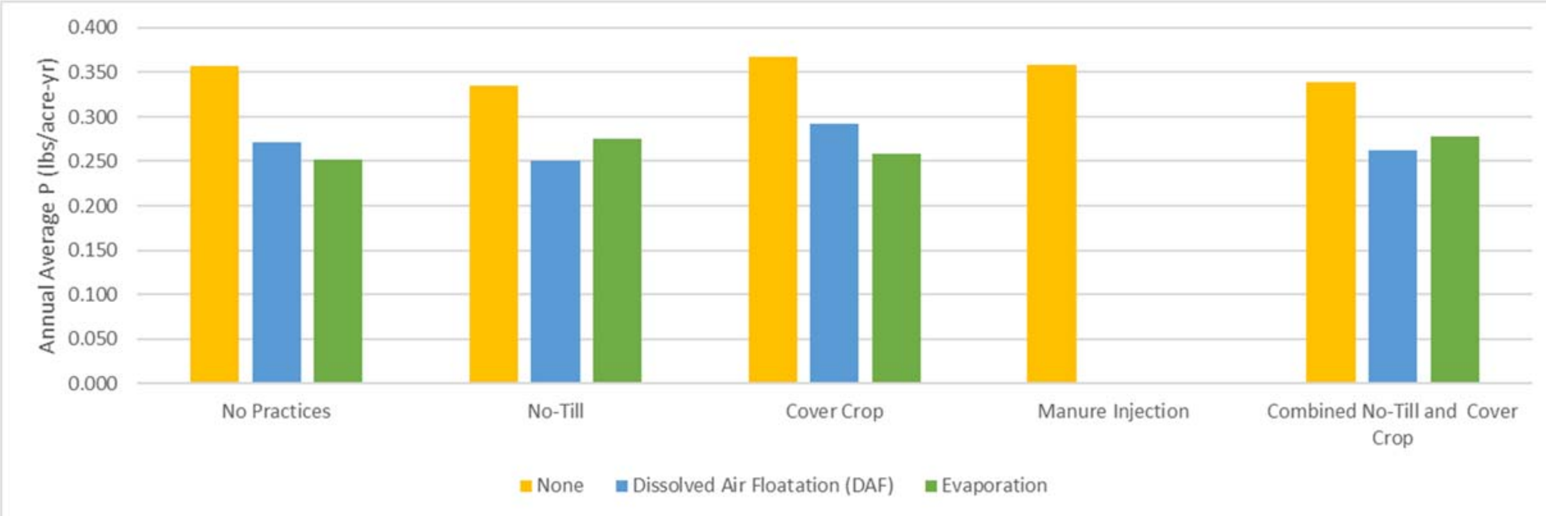

Figure 149. Annual average tile P loads for JBT01 with high P soils, based on combinations of manure management technology and conservation practices.

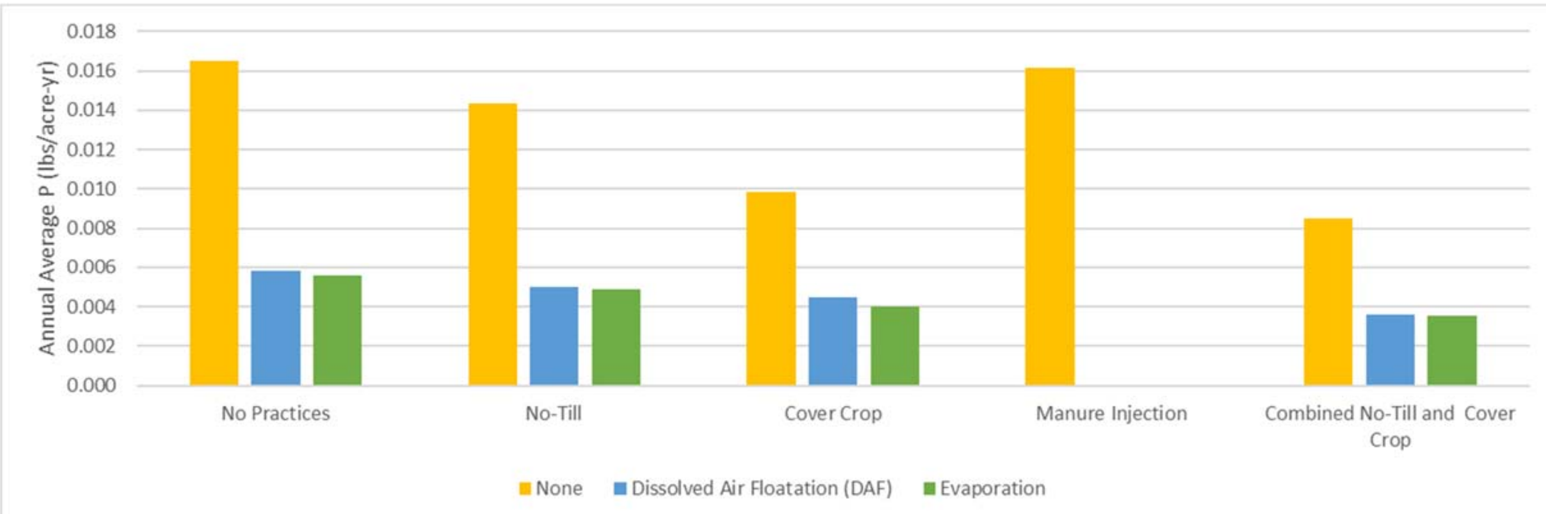

Figure 150. Annual average surface runoff soluble P loads for JBT01 with high P soils, based on combinations of manure management technology and conservation practices.

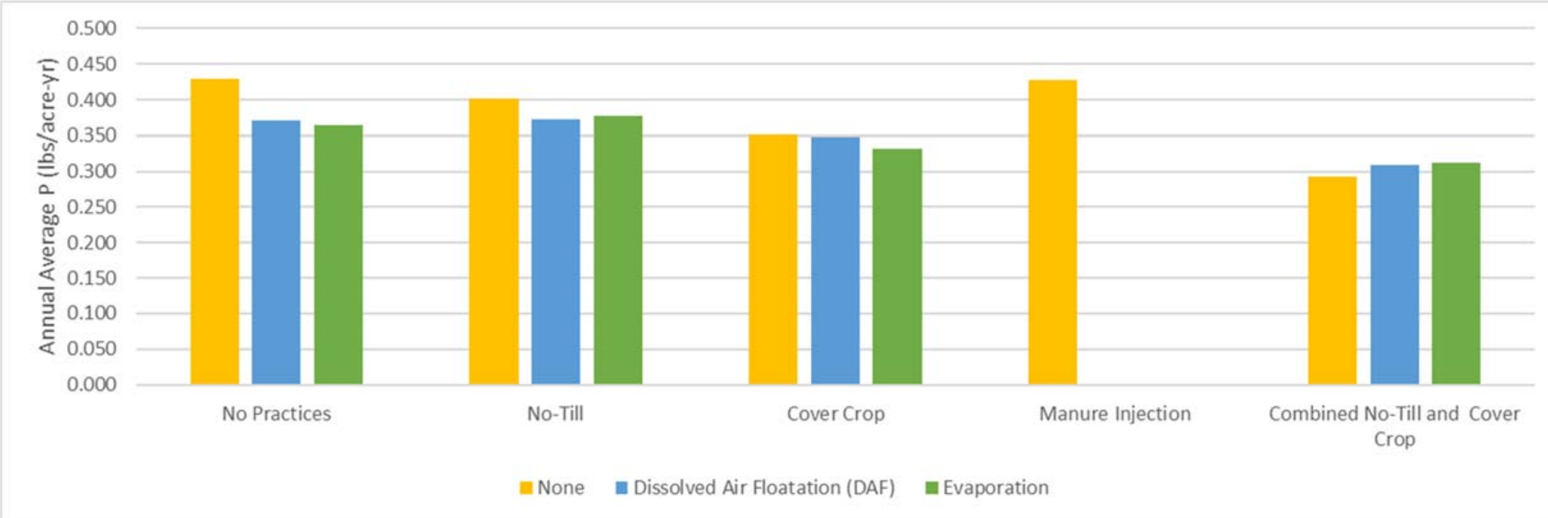

Figure 151. Annual average surface runoff sediment P loads for JBT01 with high P soils, based on combinations of manure management technology and conservation practices.

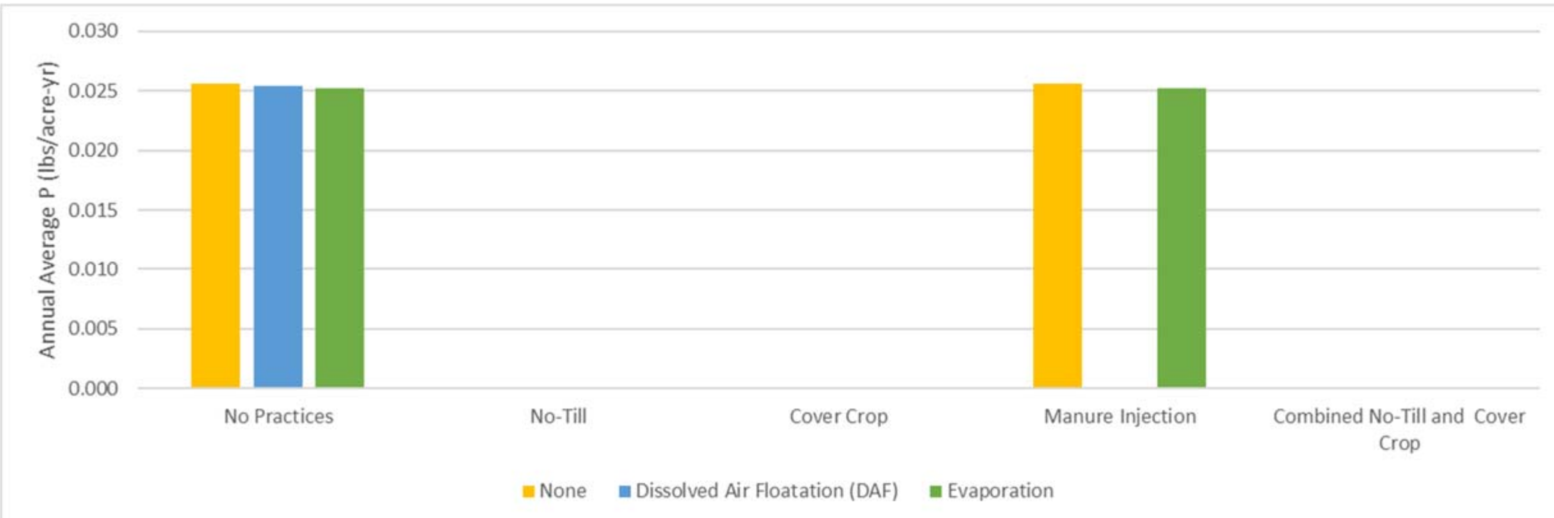

Figure 152. Annual average tile P loads for JBT11 with high P soils, based on combinations of manure management technology and conservation practices. No-till, cover crop, and combined no-till and cover crop options were not simulated for JBT11 (permanent hay).

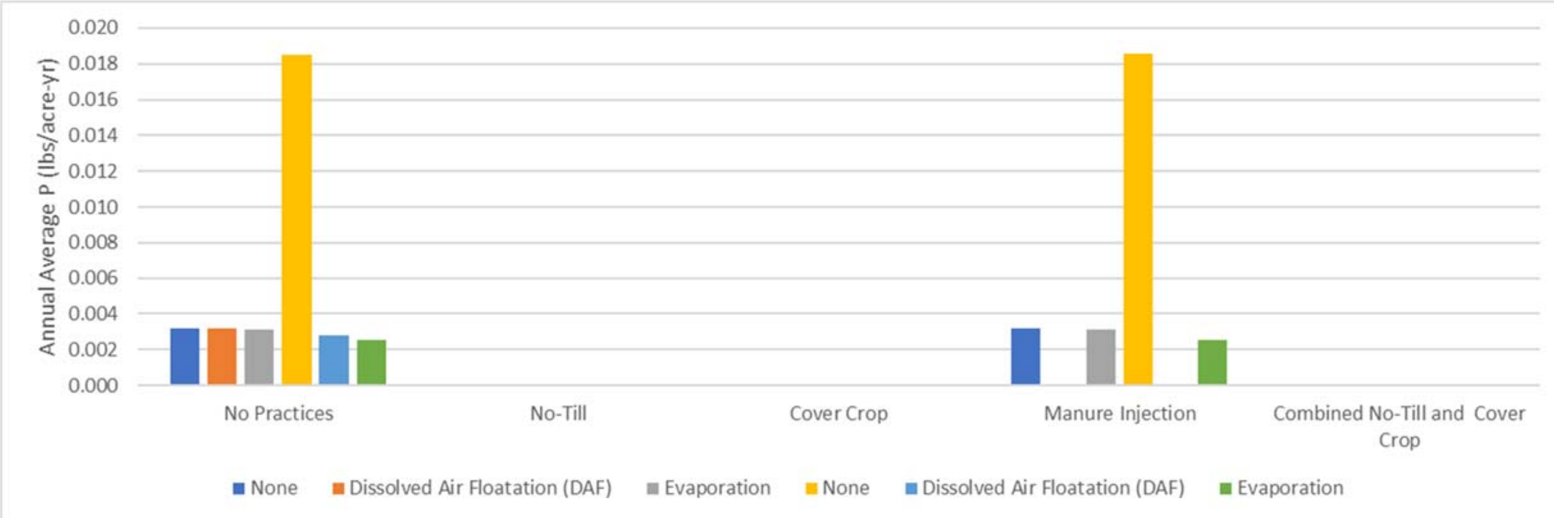

Figure 153. Annual average surface runoff soluble P loads for JBT11 with high P soils, based on combinations of manure management technology and conservation practices. No-till, cover crop, and combined no-till and cover crop options were not simulated for JBT11 (permanent hay).

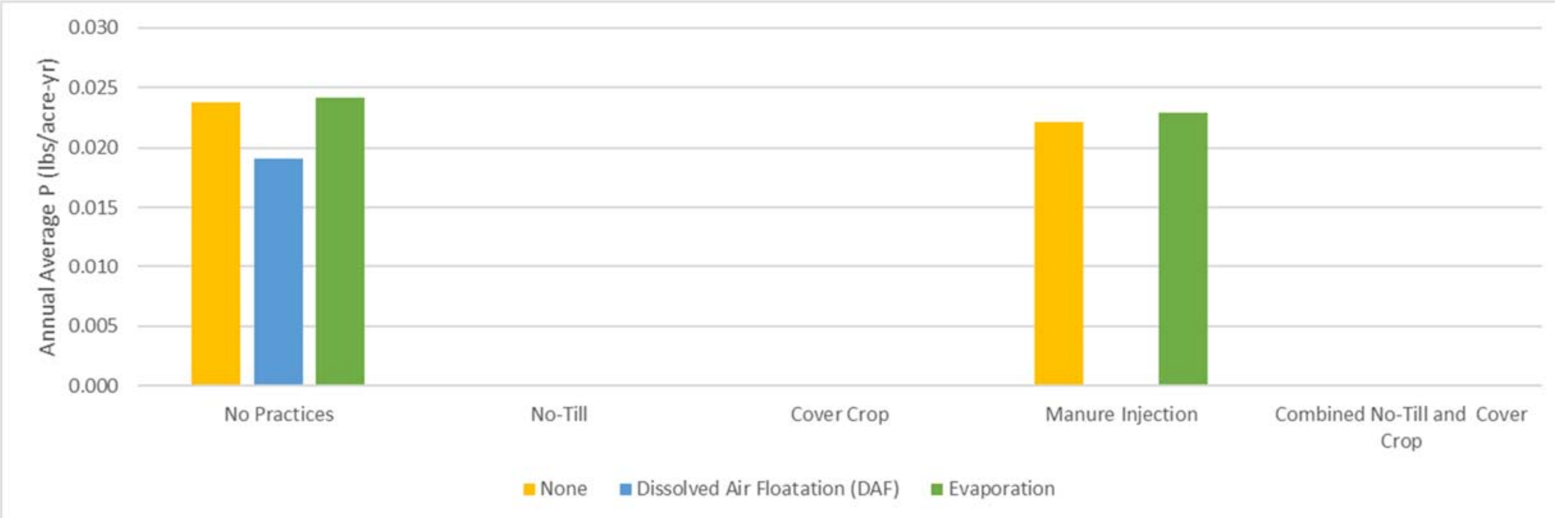

Figure 154. Annual average surface runoff sediment P loads for JBT11 with high P soils, based on combinations of manure management technology and conservation practices. No-till, cover crop, and combined no-till and cover crop options were not simulated for JBT11 (permanent hay).

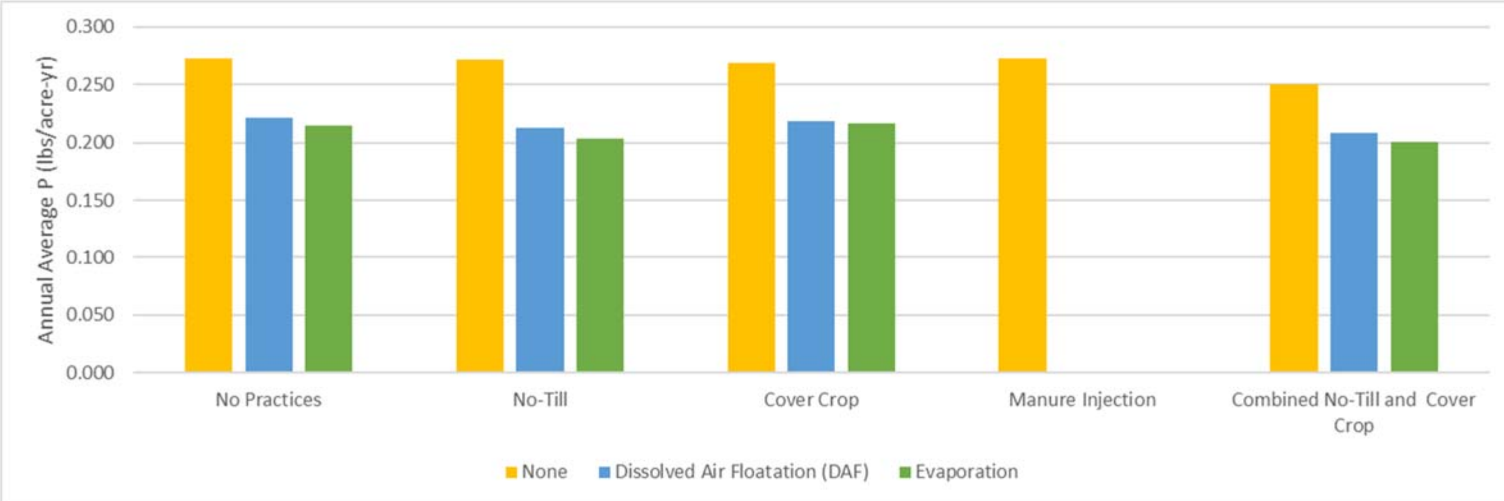

Figure 155. Annual average tile P loads for JBT18 with high P soils, based on combinations of manure management technology and conservation practices.

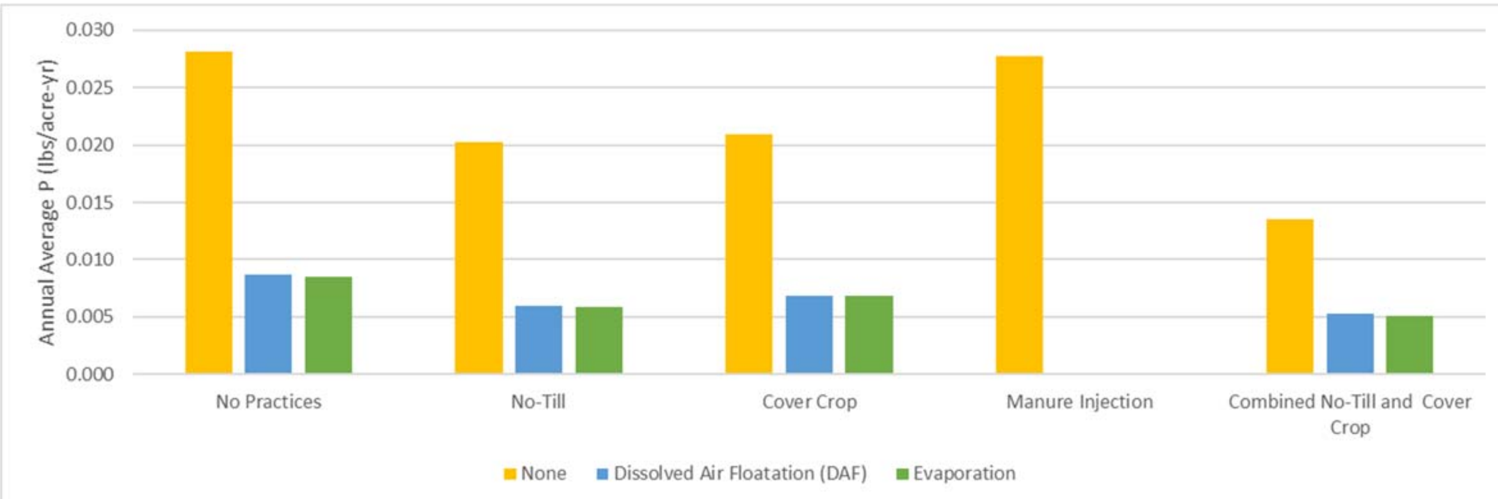

Figure 156. Annual average surface runoff soluble P loads for JBT18 with high P soils, based on combinations of manure management technology and conservation practices.

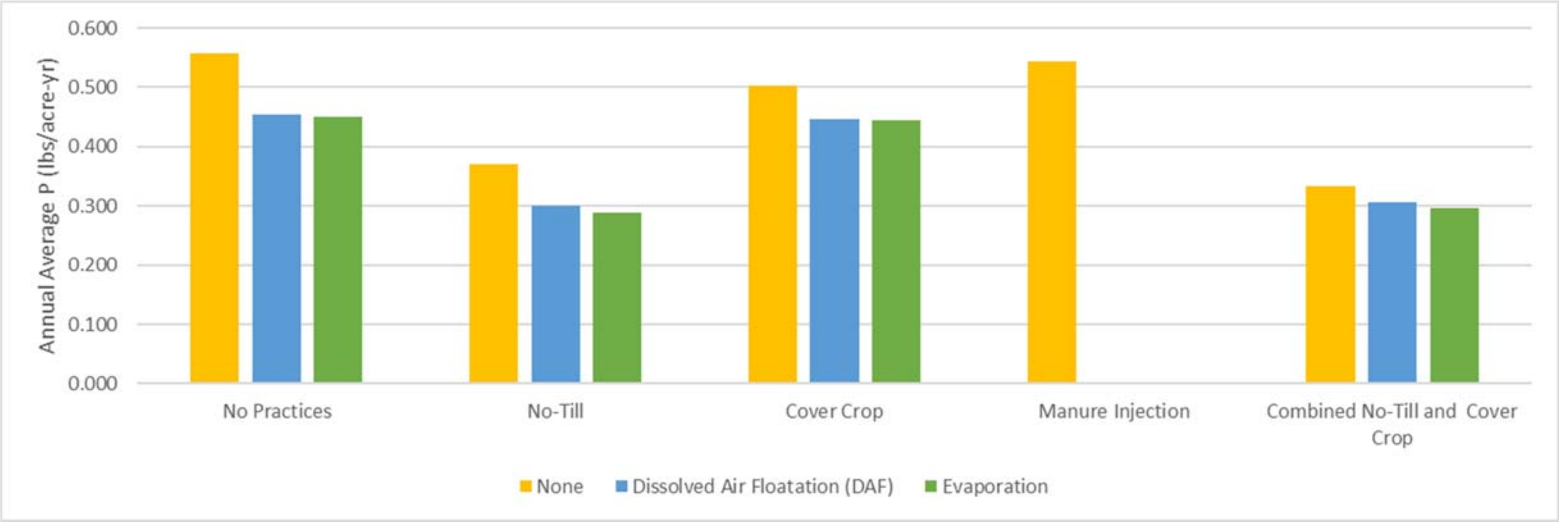

Figure 157. Annual average surface runoff sediment P for JBT18 with high P soils, based on combinations of manure management technology and conservation practices.

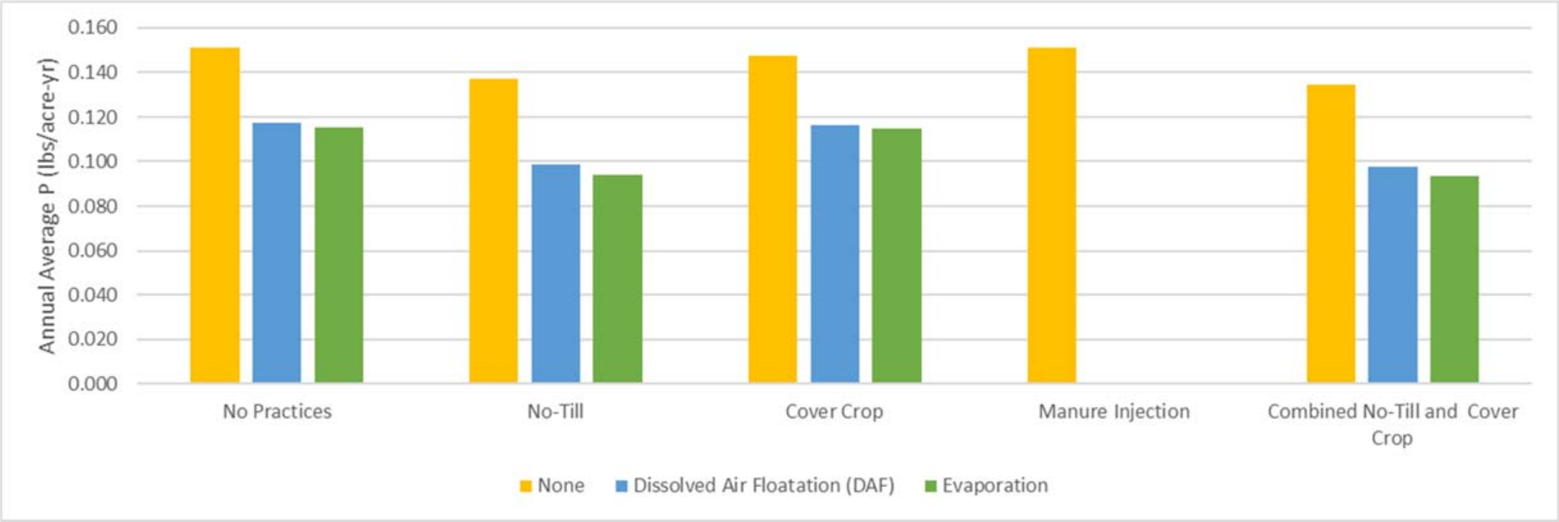

Figure 158. Annual average tile P loads for M1 with high P soils, based on combinations of manure management technology and conservation practices.

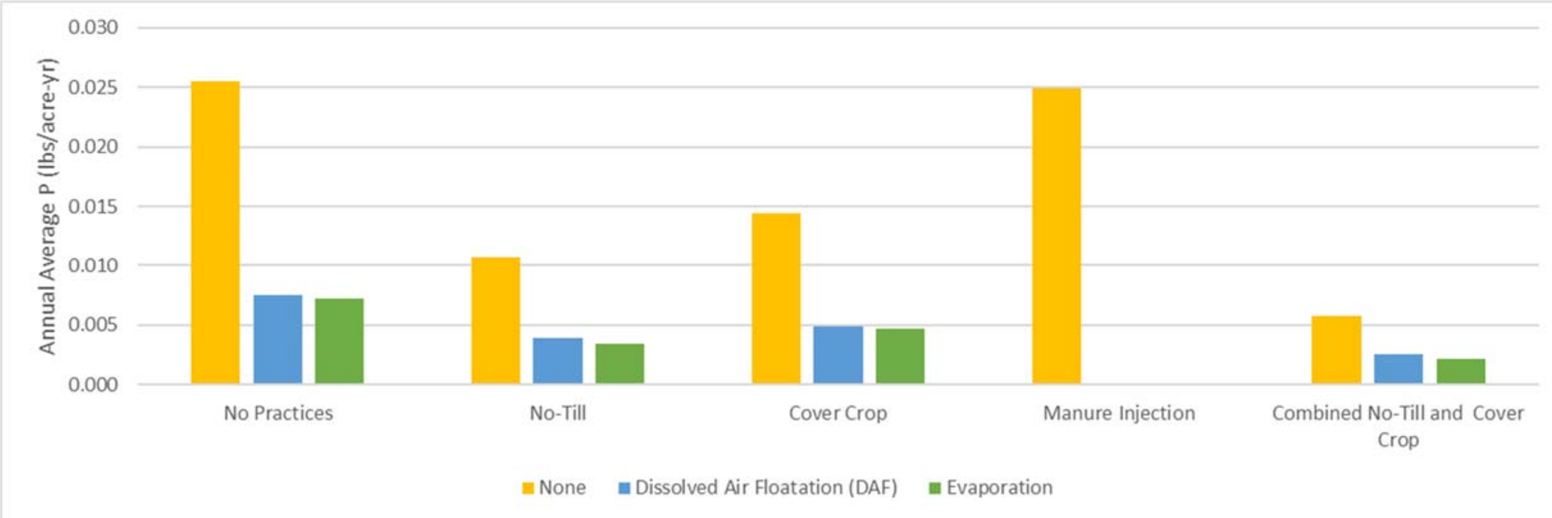

Figure 159. Annual average surface runoff soluble P loads for M1 with high P soils, based on combinations of manure management technology and conservation practices.

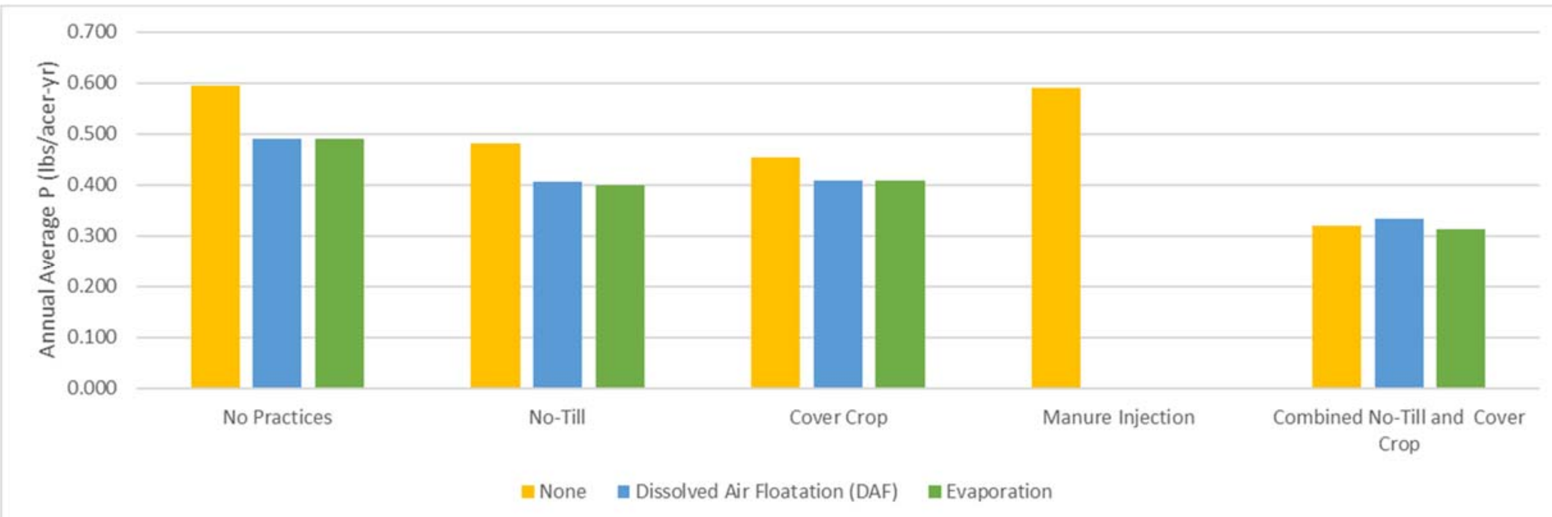

Figure 160. Annual average surface runoff sediment P loads for M1 with high P soils, based on combinations of manure management technology and conservation practices.

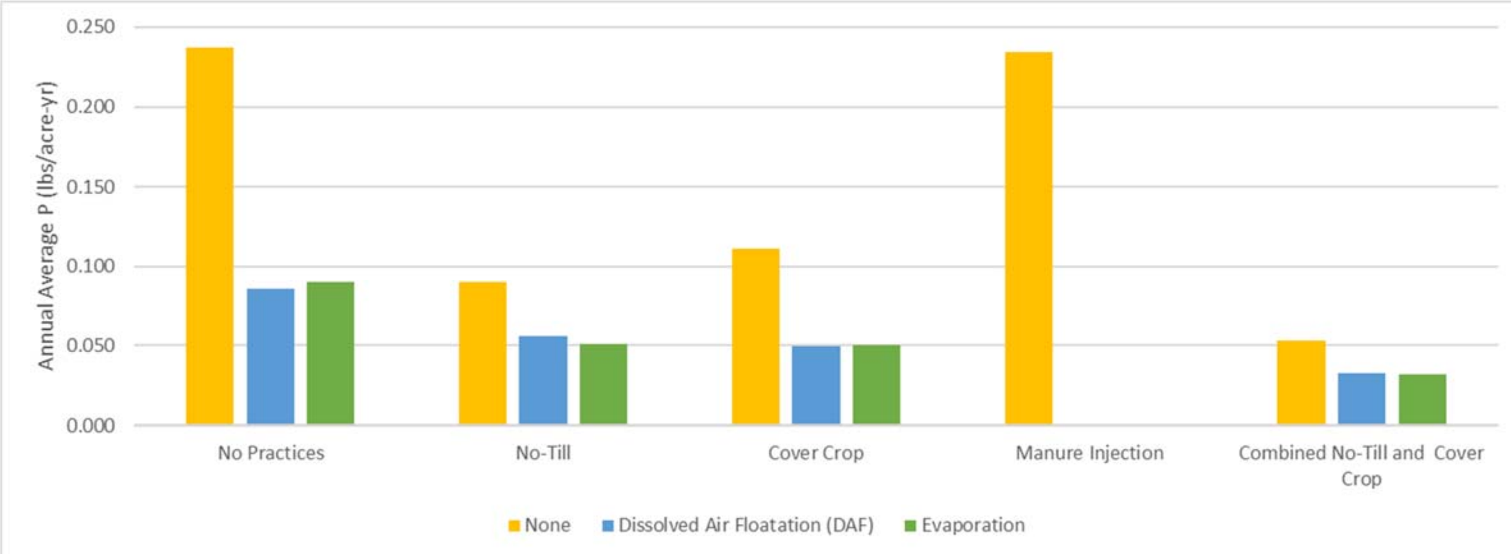

Figure 161. Annual average surface runoff soluble P loads for PAW1 with high P soils, based on combinations of manure management technology and conservation practices.

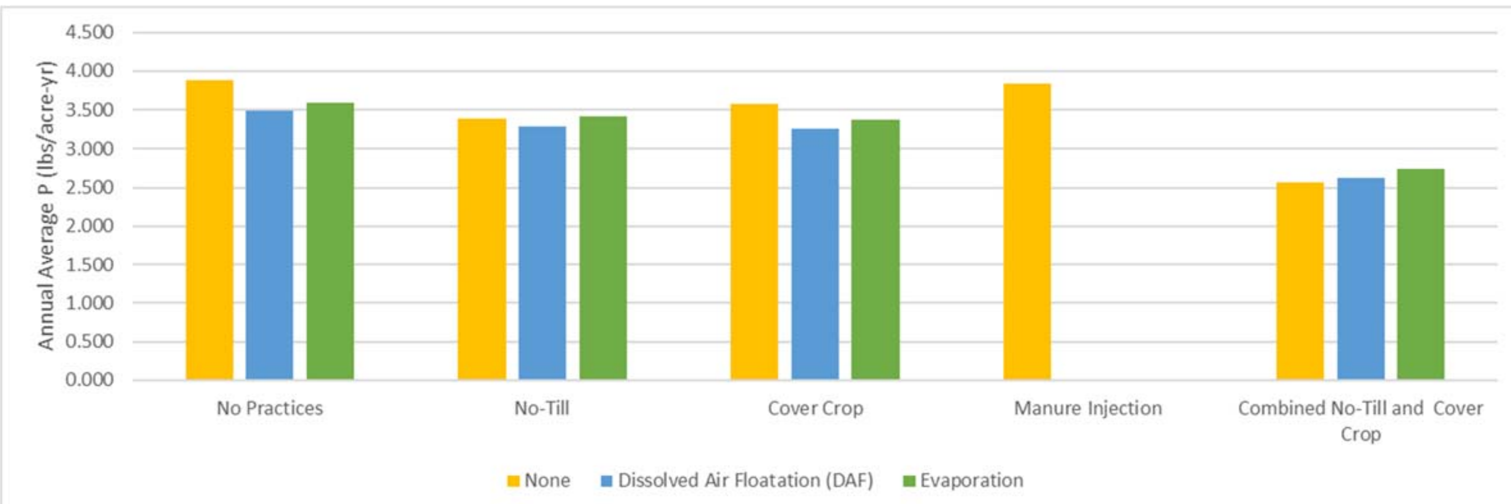

Figure 162. Annual average surface runoff sediment P loads for PAW1 with high P soils, based on combinations of manure management technology and conservation practices.