Responses to reviewers' comments

We thank referees #1 and #2 and interactive reviewer for the valuable suggestions to our manuscript. We have made major revisions in response to reviewers' comments. We recalibrated the models and rewrote the manuscript. We believe the manuscript has been greatly improved as a result of these changes. The pages and lines mentioned in the responses are related to the clean manuscript version.

Comments from Referee # 1: This paper aims to evaluate the performance of new physically based tile drainage routines proposed by Hooghoudt and Kirkham. The study is conducted in a small watershed (518 km^2) in the Midwest USA. The main objective is to compare simulated flow, tile flow, runoff, nitrate in tile flow and sediment load results for the new tile drainage routines in SWAT2012 and the old one in SWAT2009 in the LVR watershed and determine which routine provides a better model fit with observed values. Testing of the new routines and identification of parameter sets is given as the primary motivation for this research. In my opinion, the given motivation and objective add very little to the scientific knowledge, thus, do not merit publication in HESS Journal in the current form. The authors claim that the parameter set obtained from this study provide guidance for field and watershed level applications. In fact, this is not a new and significant finding. Moreover, author do not provide any discussion on physical basis of the selected parameters.

Response**:** We thank referee #1 for the suggestions to our manuscript. We incorporated discussion on the relationship between the calibrated parameters and physical process of tile drainage system, and sediment and nitrate transport in it. We also improved description of the importance of this study in introduction.

However, we do not agree that our manuscript adds very little to scientific knowledge, or this is not a new and significant finding. We agree that tile drainage modeling using SWAT has been conducted in other watersheds. However, few tile drainage modeling efforts using SWAT have been completed at both field and watershed scales, especially at fields with long term (about 12 years in this study) observed monthly tile flow, nitrate in tile flow, surface runoff, and sediment and nitrate in surface runoff data. Few previous studies have been simulated dynamics between monthly results. Moreover, the soil and weather characteristics, tile drainage system pattern, and management practices vary in different watersheds. This is the first one conducted in the LVR watershed, a typical extensively tiled watershed in the Midwest. In prior studies, RZWQM and DRAINMOD have been calibrated for crop yields, tile flow and nitrate concentration in tile flow at subsurface station, but only for five years of observed data (Singh et al., 2001a; Singh et al., 2001b). In this study, we calibrated tile drainage parameters at paired subsurface and surface stations with different tile spacing (constant tile spacing and random pattern tiles), soil characteristics, different cropping systems (reduced tillage and non-tillage), and different crop management practices. Additionally, besides calibration/validation for hydrology and water quality, we also incorporated calibration and validation for annual biomass yields of corn and soybeans, to make sure the calibrated model can accurately simulate crop growth as well.

This study is innovative and important. It is important and necessary to select an appropriate tile drainage routine suitable for modelling mildly-sloped watersheds in the Midwest with subsurface drainage systems, to accurately simulate subsurface drainage and nutrient and sediment losses, which can benefit research on reducing nitrate from agricultural watershed in the Midwest and alleviating hypoxia in the Gulf of Mexico (Jaynes and James, 2007; Kalita et al., 2007; Rabalais et al., 1999). The research results in this manuscript could provide guidance for selection of tile drainage routines and related parameter sets for tile drainage simulation at both field and watershed scales, to help solve systematic water quality issues in the old tile drainage systems. For example, well calibrated routines and related parameter sets in this study have been used for modeling of the impacts of bioenergy crop scenarios on streamflow, tile flow, sediment and nitrate losses in the LVR watershed from 1990 to 2008 (Guo *et al*., 2018), to help determine optimal bioenergy scenarios with high biomass yields, and water quality benefits in the LVR watershed and even the Mississippi River system and Gulf of Mexico. Additionally, the calibrated tile drainage parameters also have provided guidance to modeling study on the impacts of conservation practices on crop yields and nutrient reductions at USDA-ARS edge-of-field sites and other agricultural fields using the Nutrient Tracking Tool (NTT), a web-based frontend of the Agricultural Policy/Environment eXtender (APEX) in northwestern Ohio (Guo et al., 2017, unpublished), to achieve the nutrient reduction goal in Lake Erie. Moreover, research results also provided guidance to SWAT model setup and calibration for the Maumee Basin, in a project on a multi-modeling approach to help policymakers determine potential solutions to elevated phosphorus loads, and consequently harmful algal blooms (HABs) in Lake Erie (Communications with Five SWAT groups, Sep 2017). (please see related discussion in Introduction, page 3, line 9-29).

References:

Guo, T., Raj, C., Chaubey, I., Gitau, M., Arnold, J. G., Srinivasan, R., Kiniry, J. R. & Engel, B. A. (2018). Evaluation of bioenergy crop growth and the impacts of bioenergy crops on streamflow, tile drain flow and nutrient losses in an extensively tile-drained watershed using SWAT. Science of the Total Environment, 613–614 (2018) 724–735. https://doi.org/10.1016/j.scitotenv.2017.09.148

Communications with Five SWAT groups, HABRI Stakeholder Advisory Group Meeting. September 29, 2017, Heidelberg University, Tiffin, OH, USA.

Guo, T., Confesor, R., Saleh, A., & King, K. (2017). Evaluation and application of Nutrient Tracking Tool in Northwestern Ohio (manuscript).

Jaynes, D., James, D., 2007. The extent of farm drainage in the United States. Annual Meeting of the Soil and Water Conservation Society, Tampa, Florida.

Kalita, P.K., Cooke, R.A.C., Anderson, S.M., Hirschi, M.C., Mitchell, J.K., 2007. Subsurface drainage and water quality: the Illinois experience. Trans. ASABE 50 (5), 1651–1656.

Rabalais, N., Turner, R., Justic, D., Dortch, Q.,Wiseman,W., 1999. Characterization of hypoxia. Topic 1 report for the integrated assessment of hypoxia in the northern Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series Report No. 15.

Comments from Referee # 1: Some of the parameter values are also hard to understand, for instance, the range of snow fall and snow melt parameters seems too large (-5 to 5 ℃). From physical process point of view, it is hard to explain why these parameters are so different in such a small and mildly sloped watershed? To mention another example, why fitting values of SURLAG differ between sites (how scaling in hydrology may guide explaining this?). Similar can be said for other parameters like curve number, sediment and nitrogen related parameters. Therefore, the currently presented parameter sets adds very little to the available knowledge. A critical discussion on the fitted parameter values, at least explaining physical process related reasons and issues of spatial scales, is recommended.

Response**:** Yes, we agree that the range of snow fall and melt parameters were large, and calibrated parameters (eg., SURLAG) should not have large differences between sites. Thus, we recalibrated/revalidated the model at all sites. We completed multi-objective calibration of SWAT with the old and new routines using the R language. We excluded snow, groundwater and soil water process parameters and soil and site properties related parameters in calibration to avoid overcalibration (Table 2), and focused on high influence parameters determined from the previous calibration/validation using SWAT-CUP and the previous studies in the region (Boles et al., 2015; Moriasi et al., 2012; Moriasi et al., 2013), in order to obtain realistic parameter sets to represent physical processes. Given that surface runoff rarely occurred in the LVR, we also changed parameter range for SURLAG from “0.5-2.0” to “0.0-2.0”, to decrease the portion of the surface runoff release to the main channel. Generally, we obtained acceptable calibrated results with similar parameter sets in reasonable ranges at different sites (Please see Table 3).

Land use, soil, weather, patterns of tile drainage systems, and management practices are different at different stations, and thus it is reasonable to have different calibrated parameter sets for tile drainage simulation. However, parameter sets are realistic and similar to each other at different stations (Please see Table 3).

We would like to thank referee # 1 for the suggestions about a critical discussion on the fitted parameters. We have incorporated more in-depth discussion about how the calibrated parameter sets for different routines represent the physical processes of tile drainage for each indictor (please see section 3 Results and discussion). For example, for the old tile drainage routine in Rev.528 parameters, we discussed “The calibrated TDRAIN values were 26 and 25 hs for sites B and E, representing that it would take 26 and 25 hs to drain soils from saturation to field capacity at sites B and E, respectively (Table 4). The calibrated drain lag time (GDRAIN) values were 25 and 26 hs for sites B and E, representing that there were 25 and 26 hrs lag time between water enters the tiles from soil and water enters the main channel from the tiles at sites B and E, respectively, which was used to smooth the tile flow hydrograph (Table 4). However, using a draindown time (TDRAIN) to determine tile flow rate was too simplified, since TDRIAN was a static value for tiles no matter whether there was a large storm or not.” (please see page 12, lines 1-7). The calibrated parameters about the new routine in Rev.615 and Rev.645 and the improved curve number calculation method were discussed in the following two paragraphs (please see page 12, line 16-page 13, line 19). We also discussed surface runoff simulation parameters, “For Rev.615, the calibrated curve number (CN II) value (60) at sites Bs and Es was realistic for a watershed dominated by agricultural land based on the previous studies (Boles et al., 2015; Moriasi et al., 2012; Neitsch et al., 2011), and simulated surface runoff was overestimated (Figs. 4a-4b). For Rev.645, the calibrated values of newly added curve number calculation retention parameter adjustment factor (R2ADJ) were 0.81 to 0.83 at sites Bs and Es, respectively. In this case CN II value was calculated when soil water content was near saturation (Eq. (10)), which was reasonable for a mildly-sloped watershed with low runoff (Neitsch et al., 2011).” (please see page 14, lines 1-6). “The calibrated CN II values were reduced by 20 % to accurately simulate streamflow at the river station (Table 4). Moreover, the calibrated surface runoff lag coefficient (SURLAG) ranged from 0.2 to 0.3 for three revisions at all sites, representing that the model allowed a small portion of surface runoff to reach the main channel when the time of concentration is greater than one day and could smooth the simulated flow hydrograph at site R5 (Neitsch et al., 2011). The calibrated soil evaporation compensation factor (ESCO) values at five sites ranged from 0.88 to 0.91 at all sites, which meant that the reduction of ESCO would allow lower soil layers to compensate for a water deficit in upper layers and increase ET and reduce surface runoff (Jha, 2011).” (please see page 14, lines 27-34). Moreover, we discussed parameters related to sediment load simulation, “The calibrated minimum value of USLE C factor for water erosion (USLE_C) was increased from 12% to 15% for corn and from 6% to 7% for soybean at sites Bs, Es and R5 (Table 3), to increase the generation of sediment (Qiu et al., 2012). The calibrated peak rate adjustment factor for sediment routing in the subbasin (ADJ_PKR) ranged from 1.1 to 1.2 at sites Bs, Es and R5 (Table 3), which was used to adjust the amount of erosion generated in the HRUs (Neitsch et al., 2011). The exponent parameter for calculating sediment re-entrained in channel sediment routing (SPEXP) was calibrated as 1.5 for Rev.528 and Rev.615 at site R5 (Table 3), which could be used to determine the maximum amount of sediment that can be re-entrained during channel sediment routing (Sexton et al., 2011). The calibrated value of channel erodibility factor (CH_COV1) was 0.3 for Rev.528 and Rev.615 at site R5 (Table 3), which could alter channel erosion and sediment re-entrainment (Qiu et al., 2012).” (please see page 15, line 29- page 16, page 4). Additionally, the calibrated parameters for nitrate losses were also discussed, “The amount of nitrate removed from surface runoff relative to the amount removed through percolation was controlled by the nitrate percolation coefficient (NPERCO), the calibrated value of which ranged from 0.12 to 0.15 at all sites (Table 3). As NPERCO decreased from the default value (0.20) to the calibrated values, nitrate concentration in runoff would be decreased (Neitsch et al., 2011). The calibrated denitrification threshold water content (SDNCO) at all sites ranged from 0.9 to 1.1, which was in a reasonable range based on the previous studies (Boles et al., 2015; Moriasi et al., 2013) (Table 3). SDNCO was used to determine denitrification level and the calibrated SDNCO could allow reasonable amounts of denitrification to occur and then realistic amounts of nitrate to exit tiles (Boles et al., 2015; Neitsch et al., 2011). Then denitrification level could be fine-tuned by denitrification exponential rate coefficient (CDN), the calibrated values of which ranged from 0.05 to 0.06 (Table 3).” (please see page 17, lines 4-12).

References:

Boles, C. M., Frankenberger, J. R., and Moriasi, D. N.: Tile Drainage Simulation in SWAT2012: Parameterization and Evaluation in an Indiana Watershed, Trans. ASABE, 58, 1201-1213, doi: 10.13031/trans.58.10589, 2015.

Jha, M. K.: Evaluating hydrologic response of an agricultural watershed for watershed analysis, Water, 3, 604-617, 2011.

Moriasi, D., Rossi, C., Arnold, J., and Tomer, M.: Evaluating hydrology of the Soil and Water Assessment Tool (SWAT) with new tile drain equations, J Soil Water Conserv., 67, 513-524, doi: 10.2489/jswc.67.6.513, 2012.

Moriasi, D. N., Gowda, P. H., Arnold, J. G., Mulla, D. J., Ale, S., Steiner, J. L., and Tomer, M. D.: Evaluation of the Hooghoudt and Kirkham tile drain equations in the Soil and Water Assessment Tool to simulate tile flow and nitrate-nitrogen, J. Environ. Qual., 42, 1699-1710, doi:10.2134/jeq2013.01.0018, 2013.

Neitsch, S. L., Williams, J., Arnold, J., and Kiniry, J.: Soil andWater Assessment Tool Theoretical Documentation Version 2009, Grassland, Soil and Water Research Laboratory, Agricultural Research Service and Blackland Research Center, Texas Agricultural Experiment Station, College Station, Texas, 2011.

Qiu, L.-j., Zheng, F.-l., and Yin, R.-s.: SWAT-based runoff and sediment simulation in a small watershed, the loessial hilly-gullied region of China: capabilities and challenges, International Journal of Sediment Research, 27, 226-234, doi:10.1016/S1001-6279(12)60030-4, 2012.

Sexton, A., Shirmohammadi, A., Sadeghi, A., and Montas, H.: Impact of parameter uncertainty on critical SWAT output simulations, Trans. ASABE, 54, 461-471, doi: 10.13031/2013.36449, 2011.

Comments from Referee # 1: Another major problem is difficulty in following the structure of the paper. Presentation of calibration and validation results for each site demonstrates lot of repetition. This obstruct clarity and the readers could soon start feeling bored as same information comes again without any new insights and deeper discussion. One way of rectifying this issue could be by fully restructuring the paper. For example, results can be separately presented for each indicator (crop yields, flows, sediment, and nitrate) rather than per site. This can also facilitate physical explanation and scale issues when results of all sites for one indicator are combined together. For instance, when it comes to peak flow or runoff simulations, one can see where it was simulated well, at R5 or B or E etc, and then what could be the governing factors (geography, tile drainage density, variation in hydraulic conductivity, effect of CN etc).

***Response*:** We thank referee #1 for the constructive suggestions about improving the structure of the manuscript. We have reorganized the results and discussion and present results for each indicator, to avoid repetition and improve flow of the manuscript (please see section 3 Results and Discussion). We also related parameter sets with physical processes of tile drainage, and compared the performance of the old and new routines in simulating the same indicator at different sites (please see section 3 Results and discussion).

We also discussed the reasons for the performance of the old and new routines in simulating results and related it to soil and weather characteristics, tile patterns and cropping systems of sites, and physical bases of routines and parameters. For example, we discussed “The old routine in Rev.528 had different performance at sites B and E, which was mainly caused by different soil and weather characteristics, tile pattern and cropping systems of the two sites (Table 1), and the physical process of simulating tile flow in the old routine. For instance, site B had clay silt loam soil, random tile pattern and reduced-tillage practices, while site E had silt loam soil, constant tile spacing and no-tillage practices (Table 1). The old routine in Rev.528 has the potential to overestimate tile flow peaks, since simulated tile flow by the old routine was controlled by a simple drawdown time parameter (TDRAIN), and tiles were allowed to carry an unlimited maximum of water no matter how intense the rainfall. The calibrated TDRAIN values were 26 and 25 hs for sites B and E, representing that it would take 26 and 25 hs to drain soils from saturation to field capacity at sites B and E, respectively (Table 4). The calibrated drain lag time (GDRAIN) values were 25 and 26 hs for sites B and E, representing that there were 25 and 26 hrs lag time between water enters the tiles from soil and water enters the main channel from the tiles at sites B and E, respectively, which was used to smooth the tile flow hydrograph (Table 4). However, using a draindown time (TDRAIN) to determine tile flow rate was too simplified, since TDRIAN was a static value for tiles no matter whether there was a large storm or not. Thus, the old routine overestimated tile flow peaks for site E (Figs. 3c and 3d), which was consistent with tile flow simulation using the old routine in the Matson Ditch watershed in Indiana (Boles et al., 2015). Moreover, the old routine was used to simulate tile flow on days when the simulated height of the water table exceeded the height of the tile drain (Neitsch et al., 2011). Tile drainage systems can cause water table recession in tile-drained soil. Water table was lower when respiratory activity was highest in summer (Muhr et al., 2011), which may be lower than the depth of subsurface tiles during long dry summer periods. Water table depth calculation based on change in the soil water for the whole soil profile tended to overestimate the distance between water table and the soil surface when long-term simulations were performed, most commonly in cases where days without rainfall dominated (Moriasi et al., 2013). Thus, Rev.528 simulated tile flow was zero during long dry summer periods." (please see page 11, line 28 to page 12, line 15).

References:

Boles, C. M., Frankenberger, J. R., and Moriasi, D. N.: Tile Drainage Simulation in SWAT2012: Parameterization and Evaluation in an Indiana Watershed, Trans. ASABE, 58, 1201-1213, doi: 10.13031/trans.58.10589, 2015.

Moriasi, D. N., Gowda, P. H., Arnold, J. G., Mulla, D. J., Ale, S., Steiner, J. L., and Tomer, M. D.: Evaluation of the Hooghoudt and Kirkham tile drain equations in the Soil and Water Assessment Tool to simulate tile flow and nitrate-nitrogen, J. Environ. Qual., 42, 1699-1710, doi:10.2134/jeq2013.01.0018, 2013.

Muhr, J., Höhle, J., Otieno, D. O., and Borken, W.: Manipulative lowering of the water table during summer does not affect CO2 emissions and uptake in a fen in Germany, Ecol. Appl., 21, 391-401, doi:10.1890/09-1251.1, 2011.

Neitsch, S. L., Williams, J., Arnold, J., and Kiniry, J.: Soil andWater Assessment Tool Theoretical Documentation Version 2009, Grassland, Soil and Water Research Laboratory, Agricultural Research Service and Blackland Research Center, Texas Agricultural Experiment Station, College Station, Texas, 2011.

Comments from Referee # 1: Although the study mentions previous research on testing the new tile drainage routine, the results of this study are not compared with the previous findings. A detailed comparison with the previous studies would help to understand and position this work much better. While doing so, the authors should at least include topics related to parametrization, characteristics of the studied watersheds, performance evaluation results.

***Response*:** Yes, we agree that comparison between the calibrated parameters, characteristics of study areas and model performance and the previous studies is needed. The previous study on testing the new tile drainage routine evaluated performance of the routine in simulating streamflow on a tile drained watershed, without observed tile flow data at field scales. We have compared our simulated results and performance evaluation results with the previous studies on simulation of crop yields, tile flow and nitrate concentration in tile flow using DRAINMOD and Root Zone Water Quality Model (RZWQM) at field scales in the LVR. We also compared values of the calibrated parameters with the previous studies on tile drainage simulation using SWAT in other watersheds in the Midwest.

For instance, we compared crop yield simulation results at sites B and E with the previous study "Generally, simulated corn and soybean yield results were improved compared to the simulated results from Root Zone Water Quality Model (RZWQM) at sites B and E (Singh et al., 2001b), since SWAT incorporated more details of crop management practices, such as pre-plant and post-harvest fertilizer application (Neitsch et al., 2011)" (please see page 11, lines 2-4).

We also compared tile flow simulation results at sites B and E with the previous studies "The calibrated LATKSATF values for Rev.615 and Rev.645 at subsurface stations B and E, surface station Bs and Es and river station R5 ranged from 1.0 to 1.4, which were reasonable based on the previous tile drainage studies in Iowa and the recommendations value (1.4) by the Iowa Drainage Guide (Cooperative Extension Service, 1987; Singh et al., 2007; Singh et al., 2006; Singh and Helmers, 2008). Simulated monthly tile flow results for Rev.615 were better than the previous DRAINMOD and RZWQM simulated results at sites B and E (Singh et al., 2001a), since both DRAINMOD and RZWQM models overestimated daily tile flow at these sites to obtain an acceptable R^2 value (> 0.5), but they did not match well with the observed values generally from 1993 to 1998." (please see page 13, lines 16-22).

We also compared water balance results at R5 with the previous studies "Flow partitioning appeared reasonable for simulated results from Rev.528 and Rev.615 based on the previous watershed-scale tile drainage simulation studies (Boles et al., 2015; Moriasi et al., 2012; Moriasi et al., 2013)." (please see page 15, lines 15-17).

We also compared the calibrated parameters for nitrate load simulation with the previous studies "The calibrated denitrification threshold water content (SDNCO) at all sites ranged from 0.9 to 1.1, which was in a reasonable range based on the previous studies (Boles et al., 2015; Moriasi et al., 2013) (Table 3). SDNCO was used to determine denitrification level and the calibrated SDNCO could allow reasonable amounts of denitrification to occur and then realistic amounts of nitrate to exit tiles (Boles et al., 2015; Neitsch et al., 2011). Then denitrification level could be fine-tuned by denitrification exponential rate coefficient (CDN), the calibrated values of which ranged from 0.05 to 0.06 (Table 3). Generally, calibrated nitrate load in tile flow results were improved compared to nitrate concentration simulation using RZWQM and the nutrient component of DRAINMOD (DRAINMOD-N) at sites B and E (Singh et al., 2001b)." (please see page 17, lines 7-14).

References:

Boles, C. M., Frankenberger, J. R., and Moriasi, D. N.: Tile Drainage Simulation in SWAT2012: Parameterization and Evaluation in an Indiana Watershed, Trans. ASABE, 58, 1201-1213, doi: 10.13031/trans.58.10589, 2015.

Moriasi, D., Arnold, J., and Green, C.: Incorporation of Hooghoudt and Kirkham tile drain equations into SWAT2005, Proc. 4th Intl. SWAT Conf, 2005, 139-147, 2007.

Moriasi, D., Rossi, C., Arnold, J., and Tomer, M.: Evaluating hydrology of the Soil and Water Assessment Tool (SWAT) with new tile drain equations, J Soil Water Conserv., 67, 513-524, doi: 10.2489/jswc.67.6.513, 2012.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L.: Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, Trans. ASABE, 50, 885-900, 2007.

Moriasi, D. N., Gowda, P. H., Arnold, J. G., Mulla, D. J., Ale, S., Steiner, J. L., and Tomer, M. D.: Evaluation of the Hooghoudt and Kirkham tile drain equations in the Soil and Water Assessment Tool to simulate tile flow and nitrate-nitrogen, J. Environ. Qual., 42, 1699-1710, doi:10.2134/jeq2013.01.0018, 2013.

Neitsch, S. L., Williams, J., Arnold, J., and Kiniry, J.: Soil andWater Assessment Tool Theoretical Documentation Version 2009, Grassland, Soil andWater Research Laboratory, Agricultural ResearchService and Blackland Research Center, Texas Agricultural Experiment Station, College Station, Texas, 2011.

Singh, J., Kalita, P., Mitchell, J., Cooke, R., and Hirschi, M.: Simulation of tile flow for a flat tile drained watershed in east central Illinois, 2001 ASAE Annual Meeting, 1, doi: 10.13031/2013.3824, 2001a.

Singh, J., Kalita, P., Mitchell, J., Cooke, R., and Hirschi, M.: Tile water quality predictions using DRAINMOD-N and RZWQM, 2001 ASAE Annual Meeting, 1, doi: 10.13031/2013.3825, 2001b.

Comments from Referee # 1： Additionally, some very useful comments are made by S. Mylevaganam. In general, I see them valid and constructive (though critical) and could be helpful for improving the manuscript.

Response**:** We have considered the comments from Dr. Mylevaganam and improved the manuscript. Please see our responses to Dr. Mylevaganam's comments below:

Interactive comments # 1：

4) From the reader's point of view, the introduction of the manuscript needs to rewritten. In the current version of the manuscript, the introduction is built with many equations. From the reader's point of view, a section with all these equations need to be introduced after the introduction. This will help the authors to have an introduction to highlight the need of the research.

Response**:** We have moved the equations to section 2.1 Tile drainage routines in SWAT. The introduction has been reorganized to focus on the importance of the research.

Interactive comments # 1：

5) From the reader's point of view, some of the paragraphs in the introduction are not
coherent.

Response**:** We have removed information not coherent in the introduction. We have rewritten the introduction to better focus on the importance of the research.

Interactive comments # 1：

6) From the reader's point of view, the conclusions need to be re-written. Some of the words (e.g., site B, site E, and R5) in the current version of the paper need to be deleted. The actual locations of the sites need

to be mentioned in the conclusion.

***Response*:** We have deleted site name and described characteristics of the sites in the conclusions.

Interactive comments # 1：

7) In the abstract, the authors claim that both the routines provided reasonable but unsatisfactory uncalibrated flow and nitrate loss results. The authors should clearly state the meaning of "reasonable but unsatisfactory". Moreover, the authors need to state the temporal scale of their statement.

***Response*:** "Both routines provided reasonable but unsatisfactory uncalibrated flow and nitrate loss results." has been changed to "Both the old and new routines provided reasonable but unsatisfactory (NSE < 0.5) uncalibrated flow and nitrate loss results for a mildly-sloped watershed with low runoff." (please see page 1, line 20-21).

Interactive comments # 1：

8) In the abstract, the authors claim that the new routine provided acceptable simulated tile flow and nitrate in tile flow for both field sites with random pattern tile and constant tile spacing. However, in the current version of the paper, the reader is unable to find more detail about the random pattern. Moreover, it would be more meaningful if the authors relate these patterns to the adopted equations shown in equations (3-5).

***Response*:** The selected sites incorporated both random pattern tile and constant tile spacing. However, random tile spacing is still represented as a constant tile spacing in the model currently. As we mentioned, "There is an opportunity to improve the representation of tile drainage systems in SWAT, especially for individual tiles" (Please see page 18, lines 28-29). We believe that better representation of size and spatial information of tile drainage systems can improve simulation of tile drainage.

Interactive comments # 1：

9) In the current version of the paper, it is understood that there exists a coefficient named "drainage coefficient" (DC in equation-5) in SWAT 2009 and SWAT 2012. The authors also state that a coefficient named "drainage coefficient "(DRAIN_CO) was included in the new tile drainage routine in SWAT2012. Does SWAT2012 in its tile drainage routine have two drainage coefficients?

***Response*:** No, DC and DRAIN_CO are the same. We have improved the description to be consistent.

Interactive comments # 1：

10) The authors need to clearly state the difference between SWAT2012 Rev.615 and SWAT2012 Rev.645.

***Response*:** Compared to SWAT2012 Rev.615, SWAT2012 Rev.645 incorporated a new retention parameter adjustment factor (R2ADJ) to modify the soil moisture retention parameter calculation method. R2ADJ was used to modify shape coefficients, and curve number was calculated from capacity to saturation. This method is more reasonable than decreasing curve number directly (please see page 6, line 23 to page 7, line 15).

Interactive comments # 1:

11) As per the current version of the paper, a coefficient named drainage coefficient (DRAIN_CO) was included in the new tile drainage routine in SWAT2012 to "control "peak drain flow. However, in the current version of the paper, the old tile drainage routine in SWAT2009 (Rev.528) and the new tile drainage routine in SWAT2012 (Rev.615 and Rev.645) were used to simulate monthly tile flow, nitrate in tile flow, surface runoff, and sediment and nitrate in surface runoff at field sites, and monthly flow, sediment and nitrate in flow at a river station. Therefore, it is unclear about the motivation of this research work. Moreover, it would be meaningful if the authors show the equation that uses DRAIN_CO.

Response**:** The old routine in Rev.528 has the potential to overestimate tile flow peaks, since simulated tile flow by the old routine was controlled by a simple drawdown time parameter (TDRIAN), and tiles were allowed to carry an unlimited maximum of water. Thus, Rev.528 has the potential to overestimate tile flow peaks and nitrate in tile flow at site E. On the contrary, simulated tile flow peaks and nitrate in tile flow peaks from the new routine in Rev.615 and Rev.645 captured the observed values fairly well. The motivation of this research is to compare the performance of different tile drainage routines in simulating water quantity and quality at field and watershed scales, and determine the most suitable model for further simulation in the extensively tile-drained watershed. The drainage coefficient represents the maximum amount of water that can be drained from tiles. The tile flow is set equal to the drainage coefficient once tile flow is greater than drainage coefficient (please see equations on page 5, lines 9-16). We also described "(Boles et al., 2015). DRAIN_CO, the amount of water drains in 24 hs, was set as 20 mm day-1, describing the size of the main collector drain pipes and the outlet (Sui and Frankenberger, 2008)." (please see page 8, lines 19-21).

Interactive comments # 1:

12) The Fig 1 needs to be checked by a GIS professional. From the reader's point of view, the Fig 1 is meaningless. Moreover, there is an asterisk within the IL boundary. This asterisk should be related to the main figure. The abbreviation "Co." is not understood. The caption of the figure needs to be self-illustrative. The county borders also need to be checked. Do they intersect orthogonally?

Response**:** We have improved Fig.1 to better present study area information. The asterisk within the IL boundary has been removed. The abbreviation "Co." has been changed to "County". The caption of Fig.1 has been changed to "Schematic of the LVR watershed with location of monitored subsurface, surface and river stations". We have created a new Fig. 1 using county borders downloaded as an ArcGIS shapefile.

Interactive comments # 1:

13) In Fig 1, is the river station R5 shared by both the counties (i.e., Vermillion and Champaign counties)?
Response**:** Yes, the river station R5 is on the county line and shared by both counties.

14) The authors need to state few lines about the methodology used to get the drainage areas of subsurface stations and surface runoff stations.
Response**:** The drainage areas of subsurface and surface stations were determined from the hand drawn tile layout with locations of tile lines and monitoring stations at the study sites in the LVR. Please see Fig. 2 in (Singh et al., 2001)'s study. Sites B and F in Fig. 2 below represent sites B and E in current study, respectively. We have added this description in section 2.2 (please see page 6, lines 5-7).

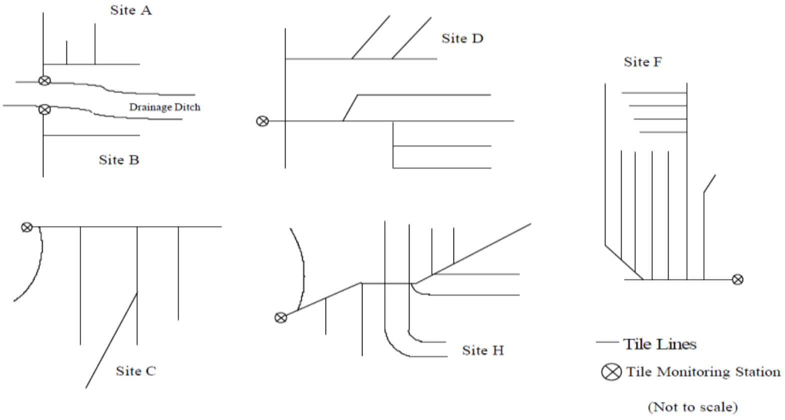

Figure. 2. Tile layout at various study sites in the LVR watershed.

Reference:
Singh, J., Kalita, P., Mitchell, J., Cooke, R., and Hirschi, M.: Simulation of tile flow for a flat tile drained watershed in east central Illinois, 2001 ASAE Annual Meeting, 1, doi: 10.13031/2013.3824, 2001.

Interactive comments # 1:
15) As per the current version of the paper (line number five on page number six), daily nitrate and sediment load was computed by multiplying water discharges with nitrate concentration (Yuan et al., 2000). How did the authors compute the daily sediment load?
Response**:** "daily nitrate and sediment load was computed by multiplying water discharges with nitrate concentration" has been changed to "daily nitrate and sediment load was computed by multiplying water discharges with nitrate and sediment concentration, respectively." (please see page 6, lines 12-13).

Interactive comments # 1：

16) As per the current version of the paper (line number eight on page number six), nitrate and sediment loads were computed by multiplying the concentration at a specific time by half the flow volume since the last concentration measurement plus half the flow volume from the concentration measurement to the next concentration measurement (Kalita et al., 2006; Yuan et al., 2000). The authors also state that nitrate and sediment concentration data were not available for "every day" that water discharge occurred. Therefore, the adopted methodology is not understood. Do the authors have nitrate and sediment concentration data every two days?

***Response*:** No, we do not have nitrate or sediment concentration data every two days. Nitrate and sediment concentration data collection was sparsely distributed. Sometimes there were concentration data for several continuous days. While sometimes there were no concentration data for a week. Generally, the nitrate and sediment concentration data were collected twice each month during the study period.

Comments from Referee # 2: The author evaluates performance of tile drainage routines in SWAT 2009 (revision 528) and 2012 (revisions 615 and 645) at two points in mildly sloped LVR watershed based on runoff, Nitrate, etc., I suggest major revision owing to following comments below: I think scientific merit of this paper can be improved from its current form by showing how (under changing climate and irrigation practices) contamination of water has changed owing to tile drainage; after setting up well calibrated routines and simulating N-contamination for long-term till last year or so.

***Response*:** We thank the referee # 2 for valuable suggestions to our manuscript. We agree that the scientific merit of our manuscript needs to be well described. We have rewritten the introduction discussed the impacts of tile drainage on water quality in the paragraph 3 of the Introduction section (please see page 2, lines 16-28). We also incorporated discussion about impacts of tile drainage systems on nitrate losses under changing precipitation (please see page 2, lines 20-23). Precipitation was sufficient in the study area and no irrigation practices were applied.

The research results in this manuscript could provide guidance for selection of tile drainage routines and related parameter sets for tile drainage simulation at both field and watershed scales. For example, well calibrated routines and related parameter sets in this study have been used for modeling of the impacts of bioenergy crop scenarios on streamflow, tile flow, sediment and nitrate losses in the LVR watershed from 1990 to 2008 (Guo *et al*., 2018).

Reference:

Guo, T., Raj, C., Chaubey, I., Gitau, M., Arnold, J. G., Srinivasan, R., Kiniry, J. R. & Engel, B. A. (2018). Evaluation of bioenergy crop growth and the impacts of bioenergy crops on streamflow, tile drain flow and nutrient losses in an extensively tile-drained watershed using SWAT. Science of the Total Environment, 613–614 (2018) 724–735. https://doi.org/10.1016/j.scitotenv.2017.09.148

ii) Author can try to discuss on how modified curve number improves SWAT 2012 tile drainage routines.

***Response*:** Yes. We incorporated discussion " For Rev.645, the calibrated values of a newly added curve number calculation retention parameter adjustment factor (R2ADJ) were 0.80 to 0.85 at sites B and E, respectively. CN II value was calculated when soil water content was near saturation (Eq. (10)), which was realistic for a mildly-sloped watershed with extensive tile drainage systems. With R2ADJ, CN II was decreased gradually based on soil from capacity to saturation, which was more reasonable than decreasing CN directly (Moriasi et al., 2013). The newly added curve number calculation retention parameter adjustment factor in Rev.645 calculates curve numbers reasonably well based on the soil moisture retention curve, and can partition surface runoff and tile flow well. Thus, simulated tile flow results from Rev.645 captured peaks well, and the differences between simulated and observed tile flow values were small after long dry periods (Figs. 3a-3d).” (please page 13, line 4-11).

iii) Fig 3c and d, Tile flow simulated from Rev.528 show constant overestimation at E and hence I feel still there is scope of improving (calibration) parameters. This may be leading to following conclusion on page 19 line4-5: old routine were better at site B, while new routine were better as site E. Difference in performance of different routines at B and E should be discussed. Is this based on different routines performing differently in different land-use at B and E or is there other physical process of routines linked to this difference.

***Response*:** We thank referee # 2 for this thought-provoking suggestion. We have recalibrated the models at all sites using the R. Calibrated tile flow at site E has been improved, but it was still unsatisfactory (Figs. 3c and 3d, Table 4). We discussed difference in performance of different routines at sties B and E “The old routine in Rev.528 had different performance at sites B and E, which was mainly caused by different soil and weather characteristics, tile pattern and cropping systems of the two sites (Table 1), and the physical process of simulating tile flow in the old routine. For instance, site B had clay silt loam soil, random tile pattern and reduced-tillage practices, while site E had silt loam soil, constant tile spacing and no-tillage practices (Table 1). The old routine in Rev.528 has the potential to overestimate tile flow peaks, since simulated tile flow by the old routine was controlled by a simple drawdown time parameter (TDRAIN), and tiles were allowed to carry an unlimited maximum of water no matter how intense the rainfall. The calibrated TDRAIN values were 26 and 25 hs for sites B and E, representing that it would take 26 and 25 hs to drain soils from saturation to field capacity at sites B and E, respectively (Table 4). The calibrated drain lag time (GDRAIN) values were 25 and 26 hs for sites B and E, representing that there were 25 and 26 hrs lag time between water enters the tiles from soil and water enters the main channel from the tiles at sites B and E, respectively, which was used to smooth the tile flow hydrograph (Table 4). However, using a draindown time (TDRAIN) to determine tile flow rate was too simplified, since TDRIAN was a static value for tiles no matter whether there was a large storm or not. Thus, the old routine overestimated tile flow peaks for site E (Figs. 3c and 3d), which was consistent with tile flow simulation using the old routine in the Matson Ditch watershed in Indiana (Boles et al., 2015). Moreover, the old routine was used to simulate tile flow on days when the simulated height of the water table exceeded the height of the tile drain (Neitsch et al., 2011). Tile drainage systems can cause water table recession in tile-drained soil. Water table was lower when respiratory activity was highest in summer (Muhr et al., 2011), which may be lower than the depth of subsurface tiles during long dry summer periods. Water table depth calculation based on change in the soil water for the whole soil profile tended to overestimate the distance between water table and the soil surface when long-term simulations were performed, most commonly in cases where days without rainfall dominated (Moriasi et al., 2013). Thus, Rev.528 simulated tile flow was zero during long dry summer periods." (please see page 11, line 28 to page 12, line 15). We also discussed simulated results and parameters for the new routine in the following paragraph.

iv) The area covered by surface and sub-surface station is as low as in range of 0.05 km2. What is HRU size corresponding to drainage area for B and E? This information will reveal how well drainage is simulated in the considered drainage area.
Response**:** Yes, we have the same concern. HRU size in SWAT is 14.18 and 0.72 km^2, respectively. HRU size in SWAT is larger than the size of the station. As we mentioned in the Limitation section, there is an opportunity to improve the representation of tile drainage systems in SWAT, especially for individual tiles. We believe that better representation of size and spatial information of tile drainage systems can improve simulation of tile drainage.

v) Leave-few-year out approach may be more suitable for calibration and validation.
Response**:** We have recalibrated models for monthly water quantity and quality results at all fields using leave-few-year out approach, which was suitable for our study. We used monthly results during the first 8-10 years (varies at different sites) for calibration and during the last two years for validation. For annual crop yields, we still used 7 years of data for calibration and 6 years of data for validation, since leave-few-year out approach would make sample points two few (two annual data) for validation (please see page 9, lines 4-11).
vi) Introduction can be reconstructed. In current form science question are repeated at two places on page 2 line 5 and page 4 line 32.
Response**:** We thank referee # 2 for the detailed suggestions to the structure and description of this manuscript. We are very grateful. The Science question on page 2 line 5 has been removed. The introduction has been reorganized to improve the flow of the manuscript and to better focus on the importance of the research.

vii) (line 20) Explanation is required on how uncalibrated routines give 'reasonable but unsatisfactory' performance.
Response**:** "Both routines provided reasonable but unsatisfactory uncalibrated flow and nitrate loss results." has been changed to "Both the old and new routines provided reasonable but unsatisfactory (NSE < 0.5) uncalibrated flow and nitrate loss results for a mildly-sloped watershed with low runoff." (please see page 1, lines 21-22).

viii) Page 5 line 25 citation is improper
Response**:** Citation on page 5 line 30 has been corrected to Mitchell et al. (2003) and Kalita et al. (2006).

ix) Page 9 line 27 variables of equation are not properly defined.

Response**:** We have changed "Where Obs and Sim represent observed and simulated data, respectively." to "Where Obs and Sim represent the ith observed and simulated monthly data, respectively. n is the total number of months. $\overline{Obs}$ and $\overline{Sim}$ represent the average values of the observed and simulated monthly data, respectively." (please see page 10, lines 3-4).

x) Repetition: Page 14 line 13-14, Two sentences can be merge in 1. Page 14-19 looks like repetition of sentences.

Response**:** The sentence on page 14 line 13-14 has been condensed to "Performance of the modelled monthly surface runoff at sites Bs and Es during the calibration and validation was satisfactory from Rev.645, and was unsatisfactory from Rev.615. " (please see page 13, lines 29-30). The sentences from page 14 to 19 have been reorganized to present results for each indicator, to avoid repetition and improve flow of the manuscript.

xi) Page 18 line 31, 'both routines' which two? Is not clear.

Response**:** Both routines represented the old tile drainage routine in SWAT2009 (Rev.528) and the new tile drainage routine in SWAT2012 (Rev.615 and Rev.645), which was mentioned on page 18, lines 31-32. We have changed 'both routines' to 'both the old and new routines'.

The list of changes made in the manuscript:

1. We developed a multi-objective calibration tool for SWAT model in the R rather than SWAT-CUP for recalibration.
2. We recalibrated the models at all sites based on the improved parameters selected for calibration, and an improved calibration/validation periods.
3. We moved the equations about tile drainage routines from the introductions to the materials and methods.
3. We rewrote the introduction to better focus on the importance of the research.
4. We reorganized the results and discussion to discuss the simulated results based on each indicator rather than each site.
5. We incorporated in-depth discussion about the calibrated parameters and tile drainage routines related to physical processes.
6. We compared the calibrated parameters and model performance with the previous studies.

These changes are shown by track changes in the marked-up manuscript version.

Comparison of performance of tile drainage routines in SWAT 2009 and 2012 in an extensively tile-drained watershed in the Midwest

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Abstract. Subsurface tile drainage systems are widely used in agricultural watersheds in the Midwestern U.S. Tile drainage systems enable the Midwest area to become highly productive agricultural lands, but can also create environmental problems, for example nitrate-N contamination associated with drainage waters. The Soil and Water Assessment Tool (SWAT) has been used to model watersheds with tile drainage. SWAT2012 revisions 615 and 645 provide new tile drainage routines. However, few studies have used these revisions to study tile drainage impacts at both field and watershed scales. Moreover, SWAT2012 revision 645 improved the soil moisture based curve number calculation method, which has not been fully tested. This study used long-term (1991-2003) field site and river station data from the Little Vermilion River (LVR) watershed to evaluate performance of tile drainage routines in SWAT2009 revision 528 (the old routine) and SWAT2012 revisions 615 and 645 (the new routine). Both the old and new routines provided reasonable but unsatisfactory (NSE < 0.5) uncalibrated flow and nitrate loss results for a mildly-sloped watershed with low runoff. The c~~C~~alibrated monthly tile flow, surface flow, nitrate-N in tile and surface flow, sediment and annual corn and soybean yield results from SWAT with the old and new tile drainage routines were compared with observed values. Generally, the new routine provided acceptable simulated tile flow (NSE = 0.~~50~~ 48 - 0.~~68~~65) and nitrate in tile flow (NSE = 0.~~50~~ 48 - 0.~~77~~68) for ~~both~~ field sites with random pattern tile and constant tile spacing, while the old routine simulated tile flow and nitrate in tile flow results for the field site with constant tile spacing were unacceptable (NSE = ~~-0.77~~0.00- ~~-0.20~~0.32 and -0.~~99~~ 29 - ~~0.21-~~0.06 respectively). The new modified curve number calculation method in revision 645 (NSE = 0.~~56~~ 50 - 0.~~82~~81) better simulated surface runoff than revision 615 (NSE = -~~5.95~~0.11 -~~∼~~ 0.5~~4~~9). The c~~C~~alibration provided reasonable parameter sets for the old and new routines in LVR watershed, and the validation results showed that the new routine has the potential to accurately simulate hydrologic processes in mildly-sloped watersheds.

1 Introduction

Subsurface drainage systems have been built up since 1870 and become common practices in agricultural watersheds in the Midwest to alleviate the damage caused by uneven drainage (Jaynes and James, 2007). ~~subsurface drainage plays an important role in water balance in the poorly drained soils of Midwestern agricultural lands.~~ Subsurface drainage allows excess water to leave the soil profile through perforated tubes installed below the soil surface. Water flows into the perforated tubes through cracks between adjacent tiles or holes in the tube and drains away when the water table is higher than the tile ~~.~~(Sugg, 2007). ~~Subsurface drainage systems are common practices in agricultural watersheds in the Midwest area of the US. With subsurface drainage systems, t~~The soil horizontal hydraulic conductivity is increased and makes water drainage from soils to ditches or subsurface drains effective; the soil vertical hydraulic conductivity ~~is so~~ large ~~that can~~ enough to prevent crop damage from flooding (Mitchell et al., 2003; Guo et al., 2012a; Guo et al., 2012b). In this way, subsurface drainage systems enable large regions of the Midwestern US to become some of the most productive agricultural lands.

Subsurface drainage plays an important role in water balance in the poorly drained soils of Midwestern agricultural lands. For instance, th~~However, intensive tile drainage systems also create environmental problems, due to contaminants like nitrate-N and pesticides in the water they transport. Thus, it is important to accurately simulate tile drains in hydrological models to correctly predict hydrologic processes and simulate the impacts of land cover and conservation practice changes at the watershed scale.~~

~~The Midwestern United States, including Illinois, Iowa, Indiana, Minnesota, Ohio, Michigan, Wisconsin and Missouri, generally have poorly drained soils. These soils remain wet after rainfall events, preventing proper field management. Plant roots are unable to obtain enough aeration in saturated soils, leading to plant growth stress and decreased yields. Consequently, extensive drainage networks have been built up in the Midwest since 1870 to alleviate the damage caused by uneven drainage (Jaynes and James, 2007). In particular, subsurface drainage plays an important role in water balance in the poorly drained soils of Midwestern agricultural lands. Subsurface drainage allows excess water to leave the soil profile through perforated tubes installed below the soil surface. Water flows into the perforated tubes through cracks between adjacent tiles or holes in the tube and drains away when the water table is higher than the tile. Tile drainage removes surplus water from fields, allows flexible field management and enhances crop production (Sugg, 2007). Tile drainage is widely used in much of the Upper Midwest area. For instance, over 40,468 km^2 (10 million acres) in Illinois have been tiled. Indiana is estimated to have more than 22,000 km^2 of land with tile drainage (Sugg, 2007). Th~~e Little Vermilion River (LVR) watershed, ~~is~~ an extensively tile-drained watershed in Illinois, has altered hydrology from an extensive subsurface drainage system network~~, in which the soil vertical hydraulic conductivity is very high and can prevent plant damage from flooding~~ ~~which is dominated by agricultural lands and with average slope reaching at most 1 %~~ (Zanardo et al., 2012). Lal et al. (1989) studied tillage-caused alterations in water balance and sediment transport for a corn-soybean rotation in Ohio, and the results demonstrated that the percentage of annual precipitation drained by tiles in plowed conditions and on no-till plots are 33 % to 58 % and 28 % to 59 %, respectively.~~The LVR watershed~~

Intensive tile drainage systems also create environmental problems, due to contaminants such as nitrate-N and pesticides in the water they transport. Subsurface drainage systems of agricultural fields in the Midwest have provided the majority of the nitrate that enters the Mississippi River and contributes to hypoxia in the Gulf of Mexico (Guo et al., 2018; Jaynes and James, 2007; Kalita et al., 2006). ~~has altered hydrology from an extensive subsurface drainage system network, in which the soil vertical hydraulic conductivity is very high and can prevent plant damage from flooding.~~

~~Subsurface drainage plays a significant role in water balance in the poorly drained soils of agricultural land, especially in the Midwestern US. For example, Lal et al. (1989) studied tillage-caused alterations in water balance and sediment transport for a corn-soybean rotation in Ohio, and the results demonstrated that the percentage of annual precipitation drained by tiles in plowed conditions and on no-till plots are 33 % to 58 % and 28 % to 59 %, respectively. In terms of water quality, in-stream nitrate loading is particularly influenced by tile drainage.~~ Subsurface tile drainage systems ~~could~~ can increase nitrate and pesticide transport, because they remove excess water ~~out of the soil surface~~ and convey soluble nitrate-N from the crop root zone. Nitrate coming from tile drains, especially for storm nitrate losses through tile drainage, has been considered the main source of nitrate in rivers and streams in the Mississippi River basin and nitrate export rate has been ~~proved~~ shown to be positively correlated to precipitation amount ($P < 0.01$) (Cuadra and Vidon, 2011)~~dwestern US~~. Additionally, 89 % - 95 % of nitrate losses in a ditch catchment were transported by the tile drainage system of the catchment (Tiemeyer et al., 2008). ~~Algoazany et al. (2007) assessed the transport of soluble P through tile drainage and surface runoff and found that crop, discharge and the interactions between sites had significant effects on soluble P concentrations in tile flow, and annual average soluble P mass loads in subsurface flow was substantially greater than that in surface runoff. Generally, agricultural land with good subsurface drainage would reduce surface runoff, soil erosion and P loss, while increasing nitrate loss.~~ Water discharge and nutrient loads of the Mississippi River ~~has~~ reduce~~d~~ light penetration, and increase~~d~~ aquatic habitat loss and hypoxia in the northern Gulf of Mexico, the largest zone of oxygen-depleted coastal waters in the US (Diaz and Solow, 1999; Rabalais et al., 1999). A decrease of nutrient loading from Mississippi River discharge could alleviate Gulf of Mexico hypoxia (Rabalais et al., 1999).

Field- and watershed-scale models have been used to evaluate nutrient reduction strategies, and it is important to accurately simulate hydrological processes of tile drainage systems for evaluation of hydrological and water quality impacts of conservation practices in watersheds in the Midwest (Guo et al., 2018). The Soil and Water Assessment Tool (SWAT), ~~is~~ a physical based and watershed-scale hydrological model, ~~.~~ has been widely used to simulate land use change impacts on water quantity and quality (Basheer et al., 2016; Guo et al., 2015; Luo et al., 2012; Shope et al., 2014; Teshager et al., 2016; Wang et al., 2016; Yin et al., 2016), but studies on simulation of tile drainage impact at field and~~the~~ watershed scales using the new tile drainage routine from SWAT2012 are few ~~(Arnold et al., 1998).~~ (Boles et al., 2015) ~~The SWAT model has been able to simulate tile drainage flow empirically since SWAT2005 (Boles et al., 2015). A new tile drainage simulation method which can accurately describe tile drainage system was used after SWAT2005 (Boles et al., 2015). Specifically, Arnold et al. (1999) enhanced SWAT2000 with a subsurface tile flow component and tested the enhanced model (SWAT2002) at a field scale with satisfactory results. However, because pothole impacts had not been included in SWAT2002 and the tile drainage routines~~

~~were old, the SWAT2002 tile drainage method was not adequate to simulate tile flow and streamflow at a watershed scale (Arnold et al., 1999; Du et al., 2005). The equation used for tile drainage simulation in SWAT2002 (Neitsch et al., 2011) is:~~

~~$tile_{wtr} = \left(SW_{ly} - FC_{ly}\right) \times (1 - exp[-24/t_{drain}])\ \ if\ SW_{ly} > FC_{ly}$ (1)~~

~~where $tile_{wtr}$ is the amount of water removed from the layer on a given day by tile drainage (mm H_2O), SW_{ly} is the water content of the layer on a given day (mm H_2O), FC_{ly} is the field capacity water content of the layer (mm H_2O), and t_{drain} is the time required to drain the soil to field capacity (hs) (Neitsch et al., 2011).~~

~~Du et al. (2005) created an impervious layer and improved the simulation of water table dynamics, and monthly flow and subsurface tile drainage simulated by SWAT2005 are much better than those simulated by SWAT2002. The time to drain soils to field capacity (TDRAIN) was used to determine the flow rate. Additionally, a new coefficient GDRAIN, the drain tile lag time, was introduced and used as the portion of the flow from tile drains into the streams on a daily basis (Du et al., 2006). Some studies have shown that the tile drainage routine in SWAT2005 could simulate the influence of subsurface drainage on hydrology at a watershed scale (Koch et al., 2013; Sui and Frankenberger, 2008). However, using a drawdown time (TDRAIN) method to simulate tile drains is simplified and limited. Equation (2) (Neitsch et al., 2011) is used for tile drainage simulation in SWAT2005:~~

~~$tile_{wtr} = (h_{wtbl} - h_{drain}/h_{wtbl}) \times (SW - FC) \times (1 - exp[-24/t_{drain}])\ \ if\ h_{wtbl} > h_{drain}$ (2)~~

~~where $tile_{wtr}$ is the amount of water removed from the layer on a given day by tile drainage (mm H_2O), h_{wtbl} is the height of the water table above the impervious zone (mm), h_{drain} is the height of the tile drain above the impervious zone (mm), SW is the water content of the profile on a given day (mm H_2O), FC is the field capacity water content of the profile (mm H_2O), and t_{drain} is the time required to drain the soil to field capacity (hs) (Neitsch et al., 2011).~~

~~A new drainage routine which includes the use of the Hooghoudt and Kirkham drainage equations was used to simulate real-world drainage systems more accurately (Moriasi et al., 2005; Moriasi et al., 2012). Based on measured streamflow data from a watershed in Iowa, SWAT with the new tile drain equations was evaluated. The water balance components were simulated, and the results showed that the modified SWAT with the Hooghoudt steady-state and Kirkham tile drain equations simulated flow well (Moriasi et al., 2012). The new tile drainage routines (Eqs. (3), (4) and (5)) added to SWAT2005 are shown below.~~

~~When the water table is below the surface and ponded depressional depths are below a threshold, the Hooghoudt steady state equation is used to compute drainage flux:~~

~~$q = 8K_e d_e m + 4K_e m^2/L^2$ (3)~~

~~where q is the drainage flux (mm h^{-1}), m is the midpoint water table height above the drain (mm), K_e is the effective lateral saturated hydraulic conductivity (mm h^{-1}), L is the distance between drains (mm), and d_e is the equivalent depth of the impermeable layer below the tile drains. When the water table completely fills the surface and ponded water remains at the surface for long periods of time, drainage flux is computed using the Kirkham equation (Moriasi et al., 2012; Moriasi et al., 2013):~~

~~$q = 4\pi K_e(t + b - r)/\delta L$ (4)~~

~~where t is the average depressional storage depth (mm), b is the depth of the tile drain from the soil surface (mm), r is the radius of the tile drain (mm), and δ is a dimensionless factor, determined by an equation developed by Kirkham (1957).~~

~~When predicted drainage flux is greater than the drainage coefficient, then the drainage flux is set equal to the drainage coefficient:~~

~~$q = DC$ (5)~~

~~where q is the drainage flux (mm h^{-1}) and DC is drainage coefficient (mm day^{-1}) (Moriasi et al., 2012; Moriasi et al., 2013).~~

~~These new tile drainage routines have been used to model tile flow at watershed scale since SWAT2009 (Boles et al., 2015). Additionally, the drainage coefficient (DRAIN_CO) was included in the new tile drainage routine in SWAT2012 to control peak drain flow. However, research on simulation of tile flow by the new tile drainage routine is limited~~(Boles et al., 2015; Du et al., 2005; Du et al., 2006; Moriasi et al., 2005; Moriasi et al., 2012). ~~Boles et al. (2015) parameterized the new tile drainage simulation method in SWAT2012 and found that peak tile flow could decrease when moving from SWAT2009 to SWAT2012, because peaks decreased and tiles flowed for a longer period of time. Thus, it is necessary to test and calibrate the new drainage routines in a tile-drained watershed and compare the modelled results by the new tile drainage routines in SWAT2012 with those by the old routines in SWAT2009. Thus, realistic parameters can be selected based on the physical condition, and the impacts of tile drainage on water balance and nutrient loading can be predicted realistically.~~

~~SWAT has been widely used to simulate land use change impacts on water quantity and quality (Basheer et al., 2016; Guo et al., 2015; Luo et al., 2012; Shope et al., 2014; Teshager et al., 2016; Wang et al., 2016; Yin et al., 2016), but studies on simulation of tile drainage impact at the watershed scale are few (Arnold et al., 1998).~~ For instance, Sui and Frankenberger (2008) quantified the impact of tile drains on nitrate loss in an extensively tile-drained watershed, and showed that simulated nitrate loss results by SWAT2005 could be used for simulation of nitrate reductions at the watershed scale. Moriasi et al. (2012) used the new tile drain equations in SWAT to evaluate hydrology of a watershed in Iowa and determined value ranges for the new tile drain parameters, finding that Hooghoudt steady-state and Kirkham tile drain equations could be alternative tile drain simulation methods in SWAT. Boles et al. (2015) tested a new tile drainage routine in a watershed in Indiana using SWAT and found that the new tile drainage routine in SWAT2012 has the potential to predict tile flow and nitrate transported by tiles.

~~Since tile drainage has impacts on hydrology and nutrient loads at the watershed scale, ~~I~~i~~t is important to accurately simulate tile drains in hydrological models to correctly predict hydrologic processes and ~~simulate impacts of land cover and conservation practice changes~~ model nutrient reduction strategies in the Mississippi River system to alleviate hypoxia in the Gulf of Mexico. ~~at the watershed scale.~~ More information about application of realistic parameters for SWAT2012 tile drainage is needed.~~, And I~~It is necessary to test and calibrate the new drainage routines in SWAT2012 and compare the modelled results with those by the old routines in SWAT2009, especially for dynamics between long-term monthly observed water quantity and quality data at both filed and watershed scales. ~~.~~

Therefore, the main objective of this study is to compare simulated flow, tile flow, runoff, nitrate in tile flow and sediment load results for the new tile drainage routines in SWAT2012 and the old one in SWAT2009 at subsurface, surface and river stations in ~~the LVR~~an extensively tile-drained watershed and determine which routine provides a better model fit with observed values, to help improve understanding of tile drainage systems and evaluate the impacts of conservation practices on nitrate load reductions at both field and watershed scales in the Mississippi River system in further research. ~~.~~We calibrated and validated SWAT models with the new and old tile drainage routines to simulate tile flow and nitrate in tile flow at subsurface stations, surface runoff, and sediment and nitrate in surface runoff at surface stations, and streamflow, and sediment and nitrate in streamflow at the river station, and compared their performance. We also considered the new tile drainage routine with the improved curve number calculation method. We then determined which tile drainage routine can provide a better model fit. The research results have been used for simulation of the impacts of bioenergy crop scenarios on streamflow, tile flow, sediment and nitrate losses in the LVR (Guo et al., 2018), ~~This~~ and also has provided guidance to the selection of parameter sets for phosphorus reduction simulation at agricultural fields in northwestern Ohio using the Agricultural Policy/Environment eXtender (APEX), to achieve the nutrient reduction goal in Lake Erie. Moreover, the research results can allow selection of the most appropriate tile drainage routine and reasonable parameter sets, to guide evaluation of performance of conservation practices in reducing nutrient loads at both field and watershed scales in mildly-sloped watersheds in the Midwest with subsurface drainage systems.~~, .~~

2 Materials and methods

2.1 Tile drainage routines in SWAT

SWAT model has simulated subsurface drainage since early versions ~~s~~(Boles et al., 2015). Specifically, Arnold et al. (1999) enhanced SWAT2000 with a subsurface tile flow component and tested the enhanced model (SWAT2002) at a field scale with satisfactory results. However, because pothole impacts had not been included in SWAT2002 and the tile drainage routines were old, the SWAT2002 tile drainage method was not adequate to simulate tile flow and streamflow at a watershed scale (Arnold et al., 1999; Du et al., 2005). The equation used for tile drainage simulation in SWAT2002 (Neitsch et al., 2011) is:

$$tile_{wtr} = \left(SW_{ly} - FC_{ly}\right) \times \left(1 - exp[-24/t_{drain}]\right) \;\; if \; SW_{ly} > FC_{ly} \quad (1)$$

where $tile_{wtr}$ is the amount of water removed from the layer on a given day by tile drainage (mm H_2O), SW_{ly} is the water content of the layer on a given day (mm H_2O), FC_{ly} is the field capacity water content of the layer (mm H_2O), and t_{drain} is the time required to drain the soil to field capacity (hs) (Neitsch et al., 2011).

Du et al. (2005) created an impervious layer and improved the simulation of water table dynamics, and monthly flow and subsurface tile drainage simulated by SWAT2005 are much better than those simulated by SWAT2002. The time to drain soils to field capacity (TDRAIN) was used to determine the flow rate. Additionally, a new coefficient GDRAIN, the drain tile lag time, was introduced and used as the portion of the flow from tile drains into the streams on a daily basis (Du et al., 2006). Some studies have shown that the tile drainage routine in SWAT2005 could simulate the influence of subsurface drainage on hydrology at a watershed scale (Koch et al., 2013; Sui and Frankenberger, 2008). However, using a drawdown time (TDRAIN) method to simulate tile drains is simplified and limited. Equation (2) (Neitsch et al., 2011) is used for tile drainage simulation in SWAT2005:

$$tile_{wtr} = (h_{wtbl} - h_{drain}/h_{wtbl}) \times (SW - FC) \times (1 - exp[-24/t_{drain}]) \ \ if \ h_{wtbl} > h_{drain} \quad (2)$$

where $tile_{wtr}$ is the amount of water removed from the layer on a given day by tile drainage (mm H_2O), h_{wtbl} is the height of the water table above the impervious zone (mm), h_{drain} is the height of the tile drain above the impervious zone (mm), SW is the water content of the profile on a given day (mm H_2O), FC is the field capacity water content of the profile (mm H_2O), and t_{drain} is the time required to drain the soil to field capacity (hs) (Neitsch et al., 2011).

A new drainage routine which includes the use of the Hooghoudt and Kirkham drainage equations was used to simulate real-world drainage systems more accurately (Moriasi et al., 2005; Moriasi et al., 2012). Based on measured streamflow data from a watershed in Iowa, SWAT with the new tile drain equations was evaluated. The water balance components were simulated, and the results showed that the modified SWAT with the Hooghoudt steady-state and Kirkham tile drain equations simulated flow well (Moriasi et al., 2012). The new tile drainage routines (Eqs. (3), (4) and (5)) added to SWAT2005 are shown below.

When the water table is below the surface and ponded depressional depths are below a threshold, the Hooghoudt steady state equation is used to compute drainage flux:

$$q = 8K_e d_e m + 4K_e m^2/L^2 \quad (3)$$

where q is the drainage flux (mm h^{-1}), m is the midpoint water table height above the drain (mm), K_e is the effective lateral saturated hydraulic conductivity (mm h^{-1}), L is the distance between drains (mm), and d_e is the equivalent depth of the impermeable layer below the tile drains. When the water table completely fills the surface and ponded water remains at the surface for long periods of time, drainage flux is computed using the Kirkham equation (Moriasi et al., 2012; Moriasi et al., 2013):

$$q = 4\pi K_e(t + b - r)/\delta L \quad (4)$$

where t is the average depressional storage depth (mm), b is the depth of the tile drain from the soil surface (mm), r is the radius of the tile drain (mm), and δ is a dimensionless factor, determined by an equation developed by Kirkham (1957).

When predicted drainage flux is greater than the drainage coefficient, then the drainage flux is set equal to the drainage coefficient:

$$q = DRAIN\_CO \quad (5)$$

where q is the drainage flux (mm h^{-1}) and DRAIN_CO is drainage coefficient (mm day^{-1}) (Moriasi et al., 2012; Moriasi et al., 2013).

These new tile drainage routines have been used to model tile flow at watershed scale since SWAT2009 (Boles et al., 2015). Additionally, the drainage coefficient (DRAIN_CO) was included in the new tile drainage routine in SWAT2012 to control peak drain flow.

2.2 Study area

The LVR watershed (Fig. 1) is located in east-central Illinois and drains approximately 518 km^2. Eighty five percent of the watershed area is in eastern Vermilion County, 13 % of the watershed is in Champaign County, and 2 % of the watershed is in Edgar County. The LVR watershed consists of flat topography, with elevations ranging from 235 meters in the headwaters to 174 meters at the watershed outlet and with average slope reaching at most 1 % (Zanardo et al., 2012) . The long-term (1991-2000) average annual precipitation for the watershed is 990 mm yr^{-1} (Kalita et al., 2006).

The watershed was subdivided into two subwatersheds, the upstream contributing areas of Georgetown Lake and the LVR. Ninety percent of the LVR watershed is agricultural land used for corn and soybean production, and the remainder consists of grassland, forest land, roadways and farmsteads (Kalita et al., 2006). Annual area planted to soybeans is equal to the area for corn planting (Algoazany et al., 2007). The dominant soil associations in the LVR watershed are Drummer silty clay loam and Flanagan silt loam (Zanardo et al., 2012; Keefer, 2003), and the dominant hydrologic soil groups are B and C.

The LVR watershed is a typical tile-drained watershed in Illinois. Water quantity and quality data for this watershed are available from a long-term (1991-2003) monitoring project through which data were collected from several subsurface stations, surface stations, river stations and wetland sites in the watershed (Mitchell et al., 2003; Kalita et al., 2006). Based on long-term field observation data (1991-2000) from the watershed, Mitchell et al. (2003) and Kalita et al. (2006) studied hydrology of flat upland watersheds in Illinois and demonstrated that the water could remain ponded on the soil surface until it would evaporate, seep or flow to the subsurface when the precipitation rate exceeds the infiltration rate of rainfall events, and surface runoff could flow into the streams directly during extremely large rainfall events.

2.3~~2~~ Sites and data for model setup

Two subsurface stations (B and E), two surface runoff stations (Bs and Es), and one river station (R5), with drainage areas of 0.03, 0.076, 0.03, 0.023, and 69 km^2, were selected for this study (Fig. 1 and Table 1). The drainage areas were determined from hand drawn tile layout with locations of tile lines and monitoring stations at the subsurface and surface stations (Singh et al., 2001a). Subsurface sites B and E were close to surface stations Bs and Es, respectively. B and E had similar land use, cropping systems and tile drainage systems with Bs and Es, respectively (Table 1). Elevation, soil, land use and weather data were used for SWAT model setup (Table 1). Daily water discharge data are available at subsurface, surface runoff, and river stations monitored by the Illinois Agricultural Experiment Station, University of Illinois at Urbana-Champaign. Water samples were obtained bi-weekly, while additional samples were taken by pump samplers during increased flow (Kalita et al., 2006). Daily nitrate and sediment load was computed by multiplying water discharges with nitrate and sediment concentration, respectively (Yuan et al., 2000). Nitrate and sediment concentrations were not available for every day that water discharge occurred, and available data contained more water discharge measurements than nitrate and sediment concentration measurements. Nitrate and sediment loads were computed by multiplying the concentration at a specific time by half the flow volume since the last concentration measurement plus half the flow volume from the concentration measurement to the next concentration measurement (Kalita et al., 2006).

Daily tile flow, surface runoff, nitrate load in tile flow, surface runoff, and streamflow, and sediment load in surface runoff and streamflow were aggregated into monthly data and adopted in this study for model calibration and validation (Table 1). Other stations were not considered due to the quality of their data (Zanardo et al., 2012). Corn and soybean planting, harvest and tillage practice data were collected from landowners (Table 1).

2.4~~3~~ Modification to the soil moisture retention parameter calculation method

The tile drainage routine based on drawdown time in SWAT2009 Revision 528 (Rev.528) was called the “old routine” in this study. The tile drainage routine based on the Hooghoudt and Kirkham equations with a DRAIN_CO in SWAT2012 Revision 615 (Rev.615) was called the “new routine” in this study. SWAT Revision 645 (Rev.645) added a retention parameter adjustment factor (R2ADJ) to Rev.615 to modify the soil moisture retention parameter calculation method (Eqs. (6) and (7)) (Neitsch et al., 2011).

$$S = 25.4(1000/CN - 10) \quad (6)$$

$$S = S_{max}(1 - SW/[SW + exp(w_1 - w_2 * SW)]) \quad (7)$$

Where S is the retention parameter for a given day (mm), CN is the curve number for the day, S_{max} is the maximum value the retention parameter can achieve on any given day (mm), SW is the soil water content of the entire profile excluding the amount of water held in the profile at wilting point (mm H_2O), and w_1 and w_2 are shape coefficients.

$$w_2 = \left(Log\left(SW_{fc}/rto3 - SW_{fc}\right) - Log\left(SW_{sa}/rtos - SW_{sa}\right)\right)/\left(SW_{sa} - SW_{fc}\right) (8)$$

$$w_1 = Log\left(SW_{fc}/rto3 - SW_{fc}\right) + \left(SW_{fc} \times w_2\right) \quad (9)$$

rto3 is the fraction difference between CN III and CN I retention parameters, rtos is the fraction difference between CN = 99 (CN_{max}) and CN I retention parameters, SW_{fc} is amount of water held in soil profile at field capacity, SW_{sa} is amount of water held in the soil profile at saturation.

In Rev.645, R2ADJ was used to modify shape coefficients, w1 and w2, to increase S and thus decrease CN. R2ADJ ranges from 0 to 1 (Eqs. (10), (11) and (12)). When R2ADJ is 0, CN II is calculated when soil water content is at field capacity. When R2ADJ is 1, CN II is calculated when soil water content is at saturation. In this case, CN is decreased gradually based on soil from capacity to saturation, which is more reasonable than decreasing CN directly. In reality, CN II could be calculated when soil water content is near saturation (CN II < 100) rather than exactly at saturation (CN II = 100) (Neitsch et al., 2011).

$$MSW_{fc} = SW_{fc} + R2ADJ \times \left(SW_{sa} - SW_{fc}\right) (10)$$

$$w_2 = \left(Log\left(MSW_{fc}/rto3 - MSW_{fc}\right) - Log\left(SW_{sa}/rtos - SW_{sa}\right)\right)/\left(SW_{sa} - MSW_{fc}\right) (11)$$

$$w_1 = Log\left(MSW_{fc}/rto3 - MSW_{fc}\right) + \left(MSW_{fc} \times w_2\right) \quad (12)$$

MSW_{fc} is the modified amount of water held in the soil profile at field capacity, and R2ADJ is the newly added retention parameter adjustment factor.

2.54 Model setup

SWAT2012 in conjunction with ArcGIS10.1 was used to simulate the LVR watershed. The 30 m National Hydrography Dataset (NHD) was used to generate a clipped stream layer for the LVR watershed into the simulation, and subbasins in the LVR watershed were delineated. Landuse data (NLCD 2006) for the study area was obtained from USGS. The National Map Viewer and SSURGO from USDA Web Soil Survey were added into ArcSWAT (Table 1). HRUs were defined using the following thresholds: 0 % landuse, 10 % soil and 0 % slope.

Daily precipitation data from rain gauge stations at sites B, E and 6 km southeast of site R5 were added in ArcSWAT and used for simulation at sites B and Bs, sites E and Es, and site R5, respectively (Table 1). Daily temperature, solar radiation, wind speed and relative humidity data from an Illinois State Water Survey (ISWS) station (Champion Station, Latitude: 40.08°, Longitude: -88.24°, Elevation: 219m) closest to the LVR watershed were used (Table 1).

Management operation data for corn and soybean growth at sties B and E were collected (Table 1). Fertilizer was applied 10 days before planting at the rates of 218 kg ha^{-1} for anhydrous ammonia and 67 kg ha^{-1} for P_2O_5. Atrazine was applied at 2.2 kg ha^{-1} three days before planting during corn growing years. P_2O_5 fertilizer was applied at 56 kg ha^{-1} 14 days before planting during soybean production years.

Tile drainage area was determined in HRUs where corn or soybeans were the current land use, slope was lower than 5 %, and soil drainage was somewhat poorly drained, poorly drained, or very poorly drained (Boles et al., 2015; Sugg, 2007; Sui and Frankenberger, 2008), and tile drained area of the LVR watershed is about 75 %.

2.6~~5~~ Parameter adjustments before model calibration

Plant growth parameters for corn and soybean growth simulation at sites B and E were adjusted. Radiation-use efficiency (BIO_E) and harvest index for optimal growing conditions (HVSTI) values for corn growth ranged from 32 to 39, and from 0.41 to 0.54, respectively, based on various studies (Edwards et al., 2005; Kiniry et al., 1998; Lindquist et al., 2005). For soybean growth, BIO_E and HVSTI values ranged from 13.2 to 25.2, and from 0.44 to 0.59, respectively (Edwards and Purcell, 2005; Mastrodomenico and Purcell, 2012; Sinclair and Muchow, 1999).

The plant growth parameters for corn and soybean growth simulation of sites B and E were adjusted (Table 2). Cibin et al. (2016) adjusted BIO_E and potential heat units (PHU) for corn growth, and PHU, minimum temperature for plant growth (T_BASE), HVSTI, normal fraction of phosphorus in yield (CPYLD) for soybean growth (Table 2) to reasonably simulate corn and soybean yields for two watersheds in the Midwest US. This study adopted the same adjustment for corn and soybean growth simulation.

For surface runoff simulation, ~~C~~curve number calculation based on the soil moisture (ICN = 0) ~~and plant ET (ICN = 1)~~ method~~s~~ w~~ere~~as included in model calibration. Tile drainage simulation parameters were adjusted for the new routine. For

Rev.615 and Rev.645, tile depth ranged from 1.05 m to 1.1 m at various sites (Drablos et al., 1988; Singh et al., 2001a), and tile depth (DDRAIN) was set as 1.075 m in the model. The maximum depressional storage selection flag/code (ISAMX) was used to control the method used to calculate the static maximum depressional storage parameter (SSTMAXD), representing the surface storage. When ISMAX is 0, SSTMAXD is allowed to be defined by the user, while when ISMAX is 1, SSTAMXD is dynamically calculated based on rainfall and tillage practices (Moriasi et al., 2005; Moriasi et al., 2012). In this study, ISMAX was set as 0 and SSTMAXD was set as 12 mm, based on the previous DRAINMOD (Skaggs et al., 2012) and SWAT studies (Boles et al., 2015). DRAIN_CO, the amount of water drains in 24 hs, was set as 20 mm day^{-1}, describing the size of the main collector drain pipes and the outlet (Sui and Frankenberger, 2008). Tile spacing (SDRAIN) for site B and site R5 was set as 28,000 mm, as same as the observed tile spacing for site E. Effective radius (RE), was used to simulate the entrance resistance into the perforations of tile drains~~ pipes~~, was set as 15 mm (Boles et al., 2015; Moriasi et al., 2012).

2.7~~6~~ Model calibration and validation

Rev.528, Rev.615 and Rev.645 simulated tile flow at sites B and E were compared with the observed values to evaluate tile drainage simulation performance of the old and new routine and the new routine with modified curve number calculation method. Rev.528 and Rev.615 simulated nitrate in tile flow at sites B and E were compared with the observed values to evaluate nitrate in tile flow simulation performance of the old and the new routines. Rev.615 and Rev.645 simulated surface runoff at site Bs and Es were compared with the observed values to evaluate surface runoff simulation performance of the default soil moisture based curve number calculation method and modified curve number calculation method. Rev.528 and Rev.645 simulated flow at site R5 were compared with the observed values to evaluate flow simulation performance of the old and new routine. Rev.645 was not used for flow simulation at river station R5, because Rev.645 could not run successfully for the mainly tile drained river station R5. This was thought to be because depth to impervious layer (DEP_IMP) values were too low and the impervious layer was too close to the soil profile, which may have affected the functionality of Rev.645 in simulating ground water and tile flow on a watershed level.

The model was run for a total of 19 years (1985-2003). The first five years (1985-1990) were for model warm-up. Model outputs, annual corn and soybean yield from 1991 to 1997, and from 1998 to 2003 at sites B and E were compared with the observed values for model calibration and validation, respectively. Monthly tile flow and nitrate in tile flow from 1992 to ~~1997~~ 2000 and from ~~1998~~ 2002 to 2003 at site B were compared with the observed values for model calibration and validation, respectively. Monthly tile flow and nitrate in tile flow from 1991 to ~~1997~~ 2000 and from ~~1998~~ 2001 to 2002 at site E were compared with the observed values for model calibration and validation, respectively. Monthly surface runoff, sediment and nitrate in surface runoff at sites Bs and Es, and monthly flow, sediment and nitrate in flow at site R5 from 1993 to ~~1997~~ 2001 and from ~~1998~~ 2002 to 2003 were compared with the observed values for model calibration and validation, respectively.

~~The~~ Multi-objective autocalibration of the model for all sites was ~~autocalibrated~~ performed ~~using~~ in Rstudio with Monte Carlo simulation (Saltelli et al., 2008)~~ SWATCUP_5.1.6.2 (SUFI-2)~~. Parameters related to surface runoff, tile drainage, evapotranspiration (ET), ~~snow, ground water, soil water,~~ sediment losses, and nitrate loss processes were selected during model calibration (Table 2). Ranges of parameters (Table 3) were determined based on the previous DRAINMOD studies in the LVR watershed (Singh et al., 2001a) and several tile drain studies in Iowa (Moriasi et al., 2012; Moriasi et al., 2013; Schilling and Helmers, 2008; Singh et al., 2007; Singh et al., 2006; Singh and Helmers, 2008) and Indiana (Boles et al., 2015). The uniform random sampling method was used to generate 2000 uniformly distributed samples for the above parameters.

For Rev.528, the calibrated values for tile flow simulation parameters at site B, time to drain soil to field capacity (TDRIAN), drain tile lag time (GDRIAN), and DEP_IMP were used for flow simulation at site R5. For Rev.615, the calibrated values for tile flow simulation parameters at site B, DEP_IMP and ~~,~~ multiplication factor to determine lateral saturated hydraulic conductivity (LATKSATF) ~~, effective radius (RE) and tile spacing (SDRAIN)~~ were modified at site R5, to accurately simulate flow and obtain reasonable water budget results.

2.8~~7~~ Model performance evaluation

Model outputs, annual corn and soybean yield, monthly tile flow and nitrate in tile flow at sites B and E, monthly surface runoff, sediment and nitrate in surface runoff at sites Bs and Es, and monthly flow, sediment and nitrate in flow at site R5 from the old and new routines were compared with observed values for model calibration and validation. Comparison between simulated results from the old and new routines and observed values were plotted. The statistical methods used for verifying model performance included Percent bias/Percent error (P_{BIAS} (%)), the coefficient of determination (R^2), the Nash-Sutcliffe model efficiency coefficient (NSE), the modified NSE (MSE) and the Kling-Gupta efficiency (KGE) (Eqs. (13), (14), (15), (16) and (17)).

$$P_{BIAS}\,[\%] = \left(\sum_{i=1}^{n}(Obs - Sim)/\sum_{i=1}^{n} Obs\right) \times 100 \quad (13)$$

$$\mathrm{NSE} = 1 - \left(\sum_{i=1}^{n}(Obs - Sim)^2/\sum_{i=1}^{n}(Obs - \overline{Obs})^2\right) \quad (14)$$

$$\mathrm{R}^2 = \left[\sum_{\mathrm{i}=1}^{\mathrm{n}}\left(\mathrm{Obs} - \overline{\mathrm{Obs}}\right)(\mathrm{Sim} - \overline{\mathrm{Sim}})\right]^2/\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{Obs} - \overline{\mathrm{Obs}})^2 \sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{Sim} - \overline{\mathrm{Sim}})^2 \quad (15)$$

$$\mathrm{MSE} = 1 - \left(\sum_{i=1}^{n}|Obs - Sim|/\sum_{i=1}^{n}\left|Obs - \overline{Obs}\right|\right) \quad (16)$$

$$\mathrm{KGE} = 1 - \sqrt{(r-1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \quad (17)$$

Where *Obs* and *Sim* represent the ith observed and simulated monthly data, respectively. ~~And~~ n is the total number of months. $\overline{Obs}$ and $\overline{Sim}$ represent the average values of the observed and simulated monthly data, respectively.~~Where Obs and Sim represent observed and simulated data, respectively.~~ $\alpha = \sigma_{Sim}/\sigma_{Obs}$, and $\beta = \mu_{Sim}/\mu_{Obs}$, and r is the linear regression coefficient between simulated and observed data (Eq. (15)).

Percent bias (Gupta et al., 1999) can measure the average tendency of the simulated data to deviate from the observed data. A value of 0.0 is optimal for P_{BIAS}, representing accurate model simulation. Negative values represent model overestimation bias, and positive values indicate model underestimation bias. If P_{BIAS} ± 25 % for streamflow, ± 55 % for sediment, and ± 70 % for N and P, model simulation results can be considered satisfactory (Moriasi et al., 2007). The R^2 value indicates the strength of the linear relationship between the simulated and observed data. A R^2 value of greater than 0.5 is considered reasonable model performance (Moriasi et al., 2007). The NSE (Nash and Sutcliffe, 1970) can represent how well the plot of observed versus simulated data fits the 1:1 line. The NSE value ranges from -∞ to 1, and the optimal value is 1. A NSE value of greater than 0.5 is considered satisfactory model performance (Moriasi et al., 2007). A NSE value of 0 means that the simulated values are as accurate as the mean of the observed data, and a negative NSE value represents that the mean value of observed data is a better predictor than the simulated data, meaning unacceptable performance (Moriasi et al., 2007). $0.36 \leq \text{NSE} \leq 0.72$ and NSE ≥ 0.75 also have been considered as satisfactory and good simulated data, respectively (Larose et al., 2007; Van Liew et al., 2003). A modified form of the NSE (Eq. (12)) could decrease the oversensitivity of the NSE to extreme values (Krause et al., 2005), and is sensitive to chronic over- or under predictions. The KGE computes the Euclidian distance of the correlation, the bias, and a measure of variability. The use of KGE (Eq. (13)) improves the bias and the variability measure considerably and decreases the correlation slightly compared to the NSE (Gupta et al., 1999). The KGE value ranges from -∞ to 1. The closer to 1, the more accurate the model is. A KGE value of greater than 0.5 is considered satisfactory simulated results (Gupta et al., 1999).

3 Results and Discussion

3.1~~2~~ Calibration and validation results for corn and soybean yields ~~subsurface stations~~

Simulated annual corn and soybean yields were compared with observed values during the calibration and validation periods at sites B and E (Fig. 2), and model performance in simulating crop yields was~~ere~~ evaluated (Table 4). Performance of the simulated corn and soybean yields from Rev.615 at sites B (Figs. 2a and 2b) and E (Figs. 2c and 2d) during the calibration and validation was satisfactory (~~Figs. 2a and 2b, and~~ Table 4). Simulated annual corn and soybean yields fit observed values well (Fig~~s~~. 2~~a and 2b~~).~~.~~ P$_{BIAS}$ values of corn and soybean yields during the calibration and validation ~~periods~~ at sites B and E ~~were~~ranged from -2 % to 13 %~~ and 2 %, respectively~~, indicating accurate model simulation. During the calibration~~ period~~, R^2, NSE, MSE and KGE values for corn and soybean yields at both sites ranged from 0.75 to~~were~~ 0.99~~, 0.91, 0.77 and 0.75, respectively~~. During the validation~~ period~~, R^2, NSE, MSE and KGE values for corn and soybean yields at both sites ranged from 0.71 to~~were~~ 0.92~~, 0.91, 0.76 and 0.89, respectively~~ (Table 4). Adjusted crop growth parameters (Table 2) in Rev.615 provided good predictions of corn and soybean yields. Generally, simulated corn and soybean yield results were improved compared to the simulated results from Root Zone Water Quality Model (RZWQM) at sites B and E (Singh et al., 2001b), since SWAT incorporated more details of crop management practices, such as pre-plant and post-harvest fertilizer application (Neitsch et al., 2011).

3.2 Calibration and validation results for tile flow, surface runoff and flow

This section outlines calibration and validation performance for monthly tile flow at ~~sites~~ subsurface stations B and E, surface runoff at surface stations ~~sites~~ Bs and Es, and flow at river station ~~site~~ R5.

3.2.1 Calibration and validation results for monthly tile flow at sites B and E

Simulated monthly tile flows were compared with observed values during~~ the~~ calibration and validation ~~periods ~~at sites B (Figs. 3a and 3b) and E (Figs. 3c and 3d~~Fig. 2~~). Model performance in simulating monthly tile flow and nitrate in tile flow at sites B and E ~~were ~~was evaluated (Table 4). Performance of the simulated monthly tile flow from Rev.528, Rev.615 and Rev.645 at site B, and Rev.615 and Rev.645 at site E during the calibration and validation was satisfactory (NSE > 0.5), except that NSE (0.48) from Rev.615 during the validation at site E was slightly under the acceptable limit (Table 4). Generally, simulated tile flow results for the old routine from Rev.528 were better than those for the new routine from Rev.615 and Rev.645 at site B. However, simulated tile flow results from Rev.615 and Rev.645 were better than those from Rev.528 at site E. ~~-~~The modified curve number calculation method in Rev.645 improved surface runoff simulation and then improved tile flow simulation compared to the default curve number calculation method based on soil moisture in Rev.615 (Figs~~s~~. ~~2c ~~3a~~-and~~ ~~2d~~3d, and Table 4). Generally, P_{BIAS} values of tile flow results ~~were 3 % and 4 % from Rev.528, 14 % and 3 % from Rev.615, and -19 % and -18 % from Rev.645~~from the three versions ranged from -16 % to 24 % during the calibration and validation ~~periods~~at two sites, ~~respectively, ~~indicating accurate model simulation, except that P_{BIAS} (-28 %) from Rev.645 during the calibration at site B, and P_{BIAS} (49 %) from Rev.528 during the validation at site E represented slightly overestimated and underestimated results, respectively. Generally, R^2, NSE~~, MSE ~~and KGE values for tile flow from the three versions were satisfactory (> 0.5), except that ~~R^2 ~~NSE (~~0.49~~< 0.5) from Rev.~~615 ~~528 during the calibration and validation and NSE (0.48) from Rev.615 during ~~during calibration period and MSE (0.48) from Rev.645 during validation period~~validation at site E were unacceptable, and slightly under the acceptable limit, respectively (Table 4).

Rev.528 simulated tile flow fit~~ted~~ observed data very well at site B (Figs. 3a and 3b, and Table 4). ~~Simulated monthly tile flow from Rev.615 and Rev.645 fit observed values well (Figs. 3c and 3d, and Table 4). ~~However, Rev.528 simulated tile flows ~~was ~~were overestimated at tile flow peaks in ~~November 1992, ~~May 1996,~~,~~ ~~March 1997 (Fig. 3c), May and ~~June ~~of ~~1998, and ~~, December 2001, and February, April and ~~May ~~of ~~2002 (Figs. ~~3d~~3c and 3d). Rev.528 simulated tile flows were underestimated from May to October in 1992, from June to November in 1994, from July in 1995 to March in 1996~~ (Fig. 3c)~~, from May in 1999 to February in 2000, from May to August in 2001, and from July to December in 2002 (Figs. ~~3d~~3c and 3d). The old routine in Rev.528 had different performance at sites B and E, which was mainly caused by different soil and ~~climatic~~weather characteristics, tile pattern and cropping systems of the two sites (Table 1), and the physical process of simulating tile flow in the old routine. For instance, site B had clay silt loam soil, random tile pattern and reduced-tillage practices, while site E had silt loam soil, constant tile spacing and no-tillage practices (Table 1). The old routine in Rev.528 has the potential to overestimate tile flow peaks, since simulated tile flow by the old routine was controlled by a simple drawdown time parameter (TDRAI~~IA~~N), and tiles were allowed to carry an unlimited maximum of water no matter how intense the rainfall. The calibrated TDRAIN values were 26 and 25 hs for sites B and E, representing that it would take 26 and 25 hs to drain soils from saturation to field capacity at sites B and E, respectively (Table 4). The calibrated drain lag time (GDRAIN) values were 25 and 26 hs for sites B and E, representing that there were 25 and 26 hrs lag time between water enters the tiles from soil and water enters the main channel from the tiles at sites B and E, respectively, which was used to smooth the tile flow hydrograph (Table 4). However, using a draindown time (TDRAIN) to determine tile flow rate was too simplified, since TDRIAN was a static value for tiles no matter whether there was a large storm or not. Thus, the old routine overestimated tile flow peaks for site E (Figs. 3c and 3d), which was consistent with tile flow simulation using the old routine in the Matson Ditch watershed in Indiana (Boles et al., 2015). ~~. -~~Moreover, ~~T~~the old routine was used to simulate tile flow on days when the simulated height of the water table exceeded the height of the tile drain (Neitsch et al., 2011). Tile drainage systems can cause water table recession in tile-drained soil. Water table was lower when respiratory activity was highest in summer (Muhr et al., 2011), which may be lower than the depth of subsurface tiles during long dry summer periods. Water table depth calculation based on change in the soil water for the whole soil profile tended to overestimate the distance between water table and the soil surface when long-term simulations were performed, most commonly in cases where days without rainfall dominated (Moriasi et al., 2013). Thus, Rev.528 simulated tile flow was zero during long dry summer periods.

The calibrated DEM_IMP for all three revisions at sites B and E ranged from 2765 to 3000 mm, representing the depth to the impervious layer, which also could determine the percent of potential seepage flows through this layer (0.0 ~ 1.0). Compared to the old routine in Rev.528, ~~The~~ the new routine in Rev.615 and Rev.645 incorporates the DRAIN_CO, and tile flow peaks can be limited by the radius of the tile. In reality, subsurface drainage systems are designed with a drainage coefficient (DRAIN_CO), which is the amount of water that can be drained in 24hs. In this case, the tiles could flow for a slightly longer ~~period of time~~period, and simulated tile flow matched well with observed values at site E (Figs. 3c and 3d). In this study, t~~T~~he more physically-based equations and the DRAIN_CO (20 mm day^{-1}) in the new routine in Rev.615 and Rev.645 can reduce the flashiness of the tile flow simulation and result in lower tile flow peak and longer recession. Moreover, the Kirkham equation was used in the new routine to calculate drainage flux when water table was lower than tiles, which improved tile drainage calculation during dry periods to the old routine. ~~-~~Simulated monthly tile flow Rev.615 was similar to observed values at two sites, except that Rev.615 simulated tile flow could not capture tile flow peaks well in May of 1996 and 1998 (Fig. 3a) and ~~February~~ May of ~~1997~~ 2002 (Fig. ~~2c~~3b) at site B. Soil moisture was reduced during long dry periods from June of 1995 to April of 1996. Subsurface tile drains can lower the water table (Sui and Frankenberger, 2008), and long-term water depletion may drop the water table lower than the depth of tiles (DDRAIN, 1075 mm). For long-term water table depth simulation (19 years in this study), the computed water table depth may gradually drop as profile soil water decreases due to periods of higher ET, which makes it harder for the water table to rise to the surface after rain events (Moriasi et al., 2013). When water storage is higher than the height of the surface storage threshold (20 % of the static maximum depressional storage (SSTMAXD), 0.24 mm in this study) and water table is near the bottom of the soil surface, the Kirkham equation is used to calculate drainage flux (Boles et al., 2015). In this study, overestimation of water table depth might have caused the new routine not to trigger the Kirkham equation to calculate tile flow drainage even though 1996 was a wet year (annual precipitation was 1008 mm). The new routine in Rev.615 resulted in decreased tile flow peaks and longer storage time (Boles et al., 2015). The new routine in Rev.645 captured tile flow peaks well at two sites, although the differences between simulated and observed tile flow values were large in ~~May 1996 and February 1997~~July 2003 at site B (Fig. ~~2c~~3a). For Rev.645, the calibrated values of a newly added curve number calculation retention parameter adjustment factor (R2ADJ) were 0.80 to 0.85 at sites B and E, respectively. CN II value was calculated when soil water content was near saturation (Eq. (10)), which was realistic for a mildly-sloped watershed with extensive~~ly~~ tile drainage systems. With R2ADJ, CN II was decreased gradually based on soil from capacity to saturation, which was more reasonable than decreasing CN directly (Moriasi et al., 2013). T~~This indicates that t~~he newly added curve number calculation retention parameter adjustment factor in Rev.645 calculates curve numbers reasonably well based on the soil moisture retention curve~~ from field capacity to saturation~~, and can partition surface runoff and tile flow well. Thus, simulated tile flow results from Rev.645 captured peaks well, and the differences between simulated and observed tile flow values were small after long dry periods (Figs. ~~2c~~3a-3d).

Besides DRAIN_CO, DDRAIN and SSTMAXD, the new routines in Rev.615 and Rev.645 incorporate~~s~~ more tile drainage simulation parameters, SDRAIN (28000 mm), RE (15 mm) and multiplication factor to determine lateral saturated hydraulic conductivity (LATKSATF), to represent tile drainage systems more realistically than the old routine in Rev.528. LATKSATF was used to determined lateral hydraulic conductivity using the saturated hydraulic conductivity for each soil layer and soil type. The calibrated LATKSATF values for Rev.615 and Rev.645 at subsurface stations B and E, surface station Bs and Es and river station R5 ranged from 1.0 to 1.4, which were reasonable based on the previous tile drainage studies in Iowa and the recommendations value (1.4) by the Iowa Drainage Guide (Cooperative Extension Service, 1987; Singh et al., 2007; Singh et al., 2006; Singh and Helmers, 2008). Simulated monthly tile flow results for Rev.615 ~~at sites B and E~~ were better than the previous DRAINMOD and ~~Root Zone Water Quality Model (~~RZWQM~~)~~ simulated results at sites B and E (Singh et al., 2001a), since both DRAINMOD and RZWQM models overestimated daily tile flow at these sites to obtain an acceptable R^2 value (> 0.5), but they did not match well with the observed values generally from 1993 to 1998. Simulated monthly tile flow results for Rev.615 at sites B and E were similar to the observed values, and obtained acceptable P_{BIAS}, R^2, NSE~~, MNS~~ and KGE generally from 1991 to 2003.

3.2.2 Calibration and validation results for monthly surface runoff at site Bs and Es

This section describes calibration and validation performance for monthly surface runoff~~, sediment and nitrate-nitrogen losses~~ at surface sites Bs and Es (Fig. 4). The LVR watershed is dominated by agricultural land with extensive tile drainage system. Direct surface runoff was a small percentage (≤ 15 %) of the stream flow in the LVR watershed, and was nearly zero for years 1995 and 1997, even though there was sufficient precipitation (Mitchell et al., 2003). Thus, it is challenging to simulate surface runoff~~, sediment load, and nutrient load in runoff~~ in the LVR watershed.

Performance of the modelled monthly surface runoff ~~from Rev.645~~ at sites Bs and Es during the calibration and validation was satisfactory from Rev.645,~~.~~ ~~Modelled monthly surface runoff from Rev.615 at site Bs during calibration and validation~~and was unsatisfactory from Rev.615. Generally, simulated surface runoff results from Rev.645 with the improved curve number calculation method were better than those from Rev.615 with the default soil moisture based curve number calculation method. Simulated surface runoff results from Rev.645 were better than those from Rev.615 for two sites~~ Bs~~ (Figs. 4a-~~ and ~~4d~~b~~, and

Table 4). Generally, simulated monthly surface runoff from Rev.645 was similar to observed values. Rev.615 simulated surface runoff results were higher than observed values (Figs. 4a-~~ and ~~4d~~b~~). For Rev.615, the calibrated curve number (CN II) value (60) at sites Bs and Es was realistic for a watershed dominated by agricultural land based on the previous studies (Boles et al., 2015; Moriasi et al., 2012; Neitsch et al., 2011), and simulated surface runoff was overestimated (Figs. 4a-4b). For Rev.645, the calibrated values of newly added curve number calculation retention parameter adjustment factor (R2ADJ) were 0.81 to 0.83 at sites Bs and Es, respectively. In this case CN II value was calculated when soil water content was near saturation (Eq. (10)), which was reasonable for a mildly-sloped watershed with low runoff (Neitsch et al., 2011). ~~For Rev.615, calibration ranges of CN2 (-20 % ~ -10 %) and calibrated CN2 value (60.1) were realistic for a watershed dominated by agricultural land (Table 3), and simulated surface runoff was overestimated (Figs. 4a and 4b).~~ P_{BIAS} values of surface runoff results from Rev.615 during the calibration and validation ~~periods ~~at two sites ranged from -143 % to -82 %~~ were -614 % and -475 %, respectively~~, representing overestimated simulation results. P_{BIAS} values of surface runoff results from Rev.645 during the calibration and validation at field site Bs were 13 % and 12 %, indicating accurate simulation results. P_{BIAS} values of surface runoff results from Rev.645 during the calibration and validation ~~periods ~~at site Es were -~~26 ~~25 % and ~~-74~~28 %, indicating slightly overestimated and overestimated simulation results, respectively. Generally, ~~R^2, ~~NSE, MSE and KGE values for simulated surface runoff results from Rev.615 at the two sites were unacceptable (< 0.5) (Table 4). R^2, NSE, MSE and KGE values for simulated surface runoff results from Rev.645 at the two sites were acceptable (> 0.5) (Table 4), except that MSE during the ~~calibration ~~validation at site Bs (0.~~48~~49) and MSE during the ~~validation ~~calibration at site Es (0.~~41~~42) ~~periods ~~were slightly under the acceptable limit~~, and the KGE value during the validation period (0.18) was unacceptable~~ (Table 4). In this watershed with flat topography and dominated by tile drainage, surface runoff was small ~~for surface station Bs ~~and nearly zero from 1994 May to 1996 March ~~(Fig. 4a) ~~and from 1999 March to 2002 April for surface station Bs (Figs. 4a and 4b)~~.~~, and nearly zero from 1994 June to 1995 April ~~(Fig. 5a) ~~and from 1998 July to 2002 March for surface station Es (Figs. ~~5b~~4c and 4d).

3.2.3 Calibration and validation results for monthly flow at site R5

~~Simulated monthly flow from Rev.528 and Rev.615 were compared with observed values during calibration and validation periods for site R5 (). Model performance of simulating flow, sediment, and nitrate load for site R5 were evaluated (Table 4).~~Performance of the modelled monthly flow from Rev.528 and Rev.615 at site R5 during ~~the ~~calibration and validation was satisfactory. Simulated monthly flow results from Rev.528 were slightly better than those from Rev.615 at site R5 (Figs. ~~6a ~~3e and ~~6b~~3f, and Table 4). Generally, simulated monthly flow was similar to observed values (Figs. ~~6a ~~3e and ~~6b~~3f). However, Rev.528 simulated flow values were higher than observed values in May 1996 and December 1997 (Fig. ~~6a~~3e), which was mainly caused by overestimation of tile flow during these periods. Simulated tile flow by the old routine in Rev.528 was controlled by a simple drawdown time parameter (TDRIAN), no matter how intense the rainfall. Thus, Rev.528 has the potential to overestimate tile flow peaks. Rev.528 and Rev.615 simulated flow values were slightly higher than observed values from June to November of 1994, 1996, ~~ and ~~1998 (Fig~~s~~. ~~6a ~~3e~~and 6b~~) and 2002 (Fig. 3f), which was mainly because of the overestimation of surface runoff during these periods. The c~~C~~alibrated~~ion~~ ~~ranges of ~~CN II~~CN2~~ values ~~(-20 % ~ -10 %) ~~were reduced by 20 % to accurately simulate streamflow at the river station (Table 4). Moreover, the calibrated surface runoff lag coefficient (SURLAG) ranged from 0.2 to 0.3 for three revisions at all sites, representing that the model allowed a small portion of surface runoff to reach the main channel when the time of concentration is greater than one day and could smooth the simulated flow hydrograph at site R5 (Neitsch et al., 2011). The calibrated soil evaporation compensation factor (ESCO) values at five sites ranged from 0.88 to 0.91 at all sites, which meant that the reduction of ESCO would allow lower soil layers to compensate for a water deficit in upper layers and increase ET and reduce surface runoff (Jha, 2011). These values were reasonable for a watershed dominated by agricultural land based on the previous studies (Boles et al., 2015; Moriasi et al., 2012; Neitsch et al., 2011)~~and plant ET curve number coefficient CNCOEF (0.5 ~ 2) were realistic for a watershed dominated by agricultural land (Table 3)~~ and have provided~~, and simulated surface runoff was overestimated~~ ~~.~~ reasonable water balance component proportions when used for modeling ~~of~~ the impacts of various bioenergy crop scenarios on hydrology and water quality in the LVR (Guo et al., 2018). Rev.528 and Rev.615 simulated flow values were lower than observed values from January 2000 to February 2001 (Fig. ~~6b~~3e), which was mainly caused by underestimation of tile flow. Since the water table was lower than the tiles after the long dry periods in 1999, the old routine in Rev.528 could not simulate tile flow, and the new routine in Rev.615 could not use the Kirkham equation to calculate tile drainage flux. P_{BIAS} values of flow results from Rev.528 ~~and Rev.615~~ during the calibration and validation ~~period~~ were -~~36~~ 16 % and -~~48~~ 20 %, respectively, representing ~~overestimated~~ fairly accurate simulation results. P_{BIAS} values of flow results from ~~Rev.528 and~~ Rev.615 during the calibration and validation ~~period~~ were -~~1~~ 26 % and -~~11~~ 37 %, respectively, indicating ~~fairly accurate~~overestimated simulation results. Generally, R^2, NSE and KGE values for simulated flow results from Rev.528 and Rev.615 were satisfactory (> 0.5), except that ~~NSE~~ MSE (0.~~48~~30) from Rev.615 during the ~~validation~~ calibration ~~period~~ was ~~slightly~~ under the acceptable limit (Table 4).

Simulated average annual tile flow values from Rev.528 (128 mm) and Rev.615 (129 mm) were 14 % and 15 % of total precipitation respectively over the period from 1992 to 2003. Simulated average annual ET values from Rev.528 (585 mm) and Rev.615 (571 mm) were 71 % and 69 % of total precipitation, respectively. Simulated average annual water yield values from Rev.528 (248 mm) and Rev.615 (265 mm) were 27 % and 29 % of total precipitation, respectively. Flow partitioning appeared reasonable for simulated results from Rev.528 and Rev.615 based on the previous watershed-scale tile drainage simulation studies (Boles et al., 2015; Moriasi et al., 2012; Moriasi et al., 2013). Major flow paths are important in determining sediment and nitrate loads.

The new tile drainage routine in Rev.615 was improved compared to the old routine in Rev.528 (Figs. ~~6~~3e and 3f, and Table 4). Rev.528 could not simulate tile flow once the water table was lower than tile depth, while Rev.615 could simulate tile flow by the Hooghoudt equation once the water table dropped after ~~a~~ long dry periods during the validation (Fig. ~~6b~~3e). Rev.615 incorporated tile parameters, such as DRAIN_CO, DDRAIN, LATKSATF, RE and SDRAIN to represent characteristics of tile drainage system, which ~~can~~ simulate tile flow more realistically. Some processes in Rev.615 could be improved. For instance, DEP_IMP can represent depth to impervious layer and soil permeability and can be separated in the model. Water table depth calculation can determine which equation will be used for tile flow simulation, and water table depth calculation during long dry periods can be improved to better simulate tile flow.

~~**Limitations of this work include limited observed rainfall data for site R5, water table depth calculation after long dry periods, and difficulty in simulating surface runoff, sediment, and nitrate in surface runoff from this extensively tile drained, mildly-sloped watershed. Observed rainfall data for site R5 was from the closest rain gauge station located 6 km southeast of site R5, which may impact the accuracy of flow simulation. There is an opportunity to improve the representation of tile drainage systems in SWAT, and improve Rev.645 functionality at watershed scales. The new routine and the improved curve number calculation method can be tested for more individual tiles and watersheds.**~~

3.3 Calibration and validation results for sediment losses in surface runoff and flow

This section outlines calibration and validation performance for monthly sediment losses in surface runoff at surface stations ~~sites~~ Bs and Es, and monthly sediment losses in~~in~~ flow at river station ~~site~~ R5. The calibrated minimum value of USLE C factor for water erosion (USLE_C) was increased from 12% to 15% for corn and from 6% to 7% for soybean at sites Bs, Es and R5 (Table 3), to increase the generation of sediment (Qiu et al., 2012). The calibrated peak rate adjustment factor for sediment routing in the subbasin (ADJ_PKR) ranged from 1.1 to 1.2 at sites Bs, Es and R5 (Table 3), which was used to adjust the amount of erosion generated in the HRUs (Neitsch et al., 2011). The e~~E~~xponent parameter for calculating sediment re-entrained in channel sediment routing (SPEXP) was calibrated as 1.5 for Rev.528 and Rev.615 at site R5 (Table 3), which could be used to determine the maximum amount of sediment that can be re-entrained during channel sediment routing (Sexton et al., 2011). The calibrated value of channel erodibility factor (CH_COV1) was 0.3 for Rev.528 and Rev.615 at site R5 (Table 3), which could alter channel erosion and sediment re-entrainment (Qiu et al., 2012).

Performance of the modelled monthly sediment load ~~in flow~~ from Rev.645 ~~for site Bs~~ was ~~satisfactory~~ reasonable during the calibration and ~~reasonable~~ satisfactory during the validation for site Bs (Figs. ~~4c~~ 5a and ~~4d, and~~5b, Table 4), and was reasonable during the calibration and validation for site Es (Figs. 5c and 5d, Table 4). Simulated monthly sediment load from Rev.645 was similar to observed values at two sites (Figs. ~~4c~~ 5a-5d~~and 4d~~), except that simulated sediment load was lower than the observed value for March 1999 at site Bs (Fig. ~~4d~~5a), and for May 1996, and April and May of 2002 at site Es (Figs. 5c and 5d). Rev.645 overestimated sediment load for June 1998 and May 2002 at site Bs (Figs. 5a and 5b), and for June 1998 at site Es (Fig. 5c). P_{BIAS} values of Rev.645 simulated sediment load results during the calibration were ~~-5~~20 % and ~~37~~ -8 % ~~from Rev.645, during calibration and validation periods~~at sites Bs and Es, respectively, indicating accurate simulation results (Table 4). P_{BIAS} values of Rev.645 simulated sediment load results during the validation were -77 % and 86 % at sites Bs and Es, indicating overestimated and underestimated simulation results, respectively (Table 4). R^2, NSE, MSE and KGE values for simulated sediment during the calibration and validation ~~period~~ were satisfactory at site Bs (> 0.5), except that R^2 (0.38) and NSE (0.27) during the calibration were under the acceptable limit (Table 4). R^2, NSE, MSE and KGE values for simulated sediment during the calibration and validation ~~period~~ were unsatisfactory site Es (< 0.5) (Table 4), except that KGE (0.78) during the calibration and R^2 (0.56) and MSE (0.50) during the validation were ~~which was because the simulated~~acceptable. Simulated sediment could not capture the sediment peak well ~~for March 1999~~at the two sites (Figs. ~~4d~~5a-5d), and performance evaluation methods are sensitive to high values. The magnitude of sediment load for the mildly-sloped sites Bs and Es was small, thus Rev.645 simulated results were reasonable even though it had difficulty in capturing sediment load peaks well ~~simulated sediment load was underestimated for March 1999~~ (Figs. 5a-5d~~4d~~).

Performance of the modelled monthly sediment load in flow from Rev.528 and Rev.615 at site R5 during the calibration and validation was reasonable (Figs. 5e and 5f, and Table 4). Simulated monthly sediment load in flow results from Rev.~~615~~ 528 were better than those from Rev.~~528~~ 615 during the calibration at site R5 (Fig~~s~~. ~~6c and 6d~~5e, and Table 4). Simulated monthly sediment load from Rev.528 and Rev.615 matched observed values fairly well, except that both the old and new routines could not capture sediment load peaks well (Figs. ~~6c~~ 5e and ~~6d~~5f). This was caused by the failure to predict surface runoff well. P_{BIAS} values of sediment load results were -~~141~~ 1916 % from Rev.528, and -~~474~~ 3004 % from Rev.615 during the validation ~~period~~, respectively, indicating overestimated model simulation ~~during validation~~ (Table 4). Generally, R^2, NSE, MSE and KGE values for simulated sediment were unsatisfactory (< 0.5), except for ~~KGE~~ R^2 (0.9~~5~~6) from Rev.~~615~~ 528 and R^2 (0.95) from Rev.615 during the ~~the calibration period~~validation~~, and R^2 (0.76) from Rev.615 during validation which~~ were acceptable (Table 4). However, the LVR watershed is a mildly-sloped watershed with extensive tile drainage systems, which was dominated by tile flow, and surface runoff and sediment in surface runoff were low, and it was challenging to simulate sediment load accurately. Rev.528 and Rev.615 simulated sediment load had difficulty in matching sediment load peaks (Figs. ~~6c~~ 5e and ~~6d~~5f), and performance evaluation results were unacceptable generally (Table 4), but simulated sediment load can still be considered reasonable, since the magnitude of sediment load in this mildly-sloped watershed was small (Figs. ~~6c~~ 5e and ~~6d~~5f).

3.4 Calibration and validation results for nitrate-nitrogen losses in tile flow, surface runoff and flow

This section outlines calibration and validation performance for monthly nitrate-nitrogen losses in tile flow at subsurface stations B and E, monthly nitrate-nitrogen losses in surface runoff at surface stations Bs and Es, and monthly nitrate-nitrogen losses in flow at river station R5. The amount of nitrate removed from surface runoff relative to the amount removed through percolation was controlled by the nitrate percolation coefficient (NPERCO), the calibrated value of which ranged from 0.12 to 0.15 at all sites (Table 3). As NPERCO decreased from the default value (0.20) to the calibrated values, nitrate concentration in runoff would be decreased (Neitsch et al., 2011). The calibrated denitrification threshold water content (SDNCO) at all sites ranged from 0.9 to 1.1, which was in ~~in~~a reasonable range based on the previous studies (Boles et al., 2015; Moriasi et al., 2013) (Table 3). SDNCO was used to determine denitrification level and the calibrated SDNCO could allow reasonable amounts of denitrification to occur and then realistic amounts of nitrate to exi~~s~~t tiles (Boles et al., 2015; Neitsch et al., 2011). Then denitrification level could be fine-tuned by denitrification exponential rate coefficient (CDN), the calibrated values of which ranged from 0.05 to 0.06 (Table 3). Generally, calibrated nitrate load in tile flow results were improved compared to nitrate concentration simulation using RZWQM and the nutrient component of DRAINMOD (DRAINMOD-N) at sites B and E (Singh et al., 2001b).

Performance of the simulated monthly nitrate in tile flow from Rev.528 at site B and Rev.615 at sites B and E during the calibration and validation was satisfactory, and from Rev528 at site E during the calibration and validation it was unsatisfactory

(Figs. 6a-6d, and Table 4).~~.~~ ~~Performance of the modelled monthly nitrate in tile flow from Rev.528 for site E during calibration and validation was unsatisfactory (Figs. 3e and 3f), which is likely caused by the failure to predict accurate tile flow (Figs. 3c and 3d).~~Generally, simulated nitrate in tile flow results ~~by~~ for the old routine from Rev.528 were slightly better than those ~~by~~ for the new routine from Rev.615 at site B (Figs. ~~2e~~ 6a and ~~2f~~6b, and Table 4). However, simulated nitrate in tile flow results for the new routine were better than those for the old routine at site E (Figs. 6c and 6d, and Table 4). ~~Simulated~~Generally, simulated monthly nitrate in tile flow matched observed values well, except that Rev.528 and Rev.615 simulated nitrate in tile flow at site B could not capture peaks well in May 1996, ~~and~~ February 1997 and May 2002 (Figs. ~~2e~~6a and 6b), and Rev.615 simulated nitrate in tile flow at site E was overestimated in November and December 1994 and April 2001, and underestimated in in July 1992, May 1995, and from May to October 2002 (Figs. 6c and 6d), which was caused by the failure to predict tile flow correctly during these periods (Figs. ~~2e~~3a and 3b). Generally, Rev.528 simulated nitrate in tile flow at site E during the calibration and validation was underestimated (Figs. 6c and 6d), which was likely caused by the failure to predict accurate tile flow (Figs. 3c and 3d). ~~-~~P_{BIAS} values of nitrate in tile flow results from Rev.528 and Rev.615 at site B and Rev.615 at site E ~~were 8 % and 23 % from Rev.528, and 33 % and 18 % from Rev.615~~ during the calibration and validation ~~periods~~ranged from 24 % to 39 %, ~~, respectively,~~ indicating accurate model simulation (Table 4). Generally, R^2, NSE, MSE and KGE values for simulated nitrate in tile flow from Rev.528 and Rev.615 at site B and Rev.615 at site E~~-~~ were satisfactory (> 0.5). However, ~~R^2 (0.37) and~~ NSE (0.48~~22~~) from Rev.615 during the ~~calibration period~~ validation at site E was slightly under the acceptable limit~~ere not satisfactory~~, and MSE from Rev.615 during the calibration (0.32) and validation (0.31~~43~~) at site E ~~and KGE (0.48) from Rev.615 during the calibration period~~ were ~~slightly under the acceptable limit~~unacceptable (Table 4), which was due to underestimated nitrate values in tile flow after long dry periods (Figs. ~~2e~~6c and 6d). R^2, NSE, MSE and KGE values for simulated nitrate in tile flow from Rev.528 at site E were unsatisfactory (< 0.5), except that R^2 (0.5) during the validation was acceptable.

Performance of the modelled monthly nitrate load in surface runoff from Rev.645 at~~for~~ site Bs during the calibration and validation and at site Es during the calibration was reasonable, and at Es during the validation was satisfactory (Figs. ~~4e and 4f~~7a-7d, and Table 4). Simulated monthly nitrate load was similar to observed values ~~(Figs. 4e and 4f)~~, except that simulated nitrate load values were lower than the observed values in May of 1996 and 1998, ~~and~~ January 1999 and May 2002 at site Bs (Figs. ~~4e~~ 7a and ~~4f~~7b), in May 1996, April 1999, June 2000, October 2001 and April and May 2002~~0~~ at site Es, ~~.~~ P_{BIAS} values of nitrate load results ~~were 79 % and 53 %~~ranged from 59 % to 99 % during the calibration and validation ~~periods~~at sites Bs and Es, indicating underestimated model simulation. Generally, R^2, NSE, MSE and KGE values for simulated nitrate load during the calibration and validation at site Bs and during the calibration at site Es were unsatisfactory (< 0.5), except that MSE (0.54) and KGE (0.55) during the validation at site Bs were acceptable (Table 4). R^2, NSE, and MSE values for simulated nitrate load during the validation at site Es were satisfactory (> 0.5) (Table 4). ~~However,~~ Rev.645 simulated nitrate in surface flows at sites Bs and Es were~~as~~ reasonable, as nitrate in surface runoff was low given the watershed was dominated by tile flow and surface runoff rarely occurred.~~.~~

Performance of the modelled monthly nitrate load in flow from Rev.528 and Rev.615 at site R5 during the calibration and validation was satisfactory (Figs. 6e and 6f, and Table 4). ~~.~~Simulated monthly nitrate loads in flow results from Rev.615 were better than those from Rev.528 ~~at site R5~~during the calibration, and Rev.528 simulated results were better than those from Rev.615 during the validation at site R5 (Figs. 6e and 6f, and Table 4). Simulated monthly nitrate load was similar to observed values, except that Rev.528 simulated nitrate load values were higher than observed values in May 1996, December 1997, and May 2002 (Figs. 6e and 6f), which was mainly caused by overestimation of tile flow during these periods. Rev.528 and Rev.615 simulated nitrate load values were lower than observed values during June 1997, January and February of 1999, May and June of 2000, and ~~May and~~ June ~~of~~ 2002 (Figs. 6e and 6f), which was mainly caused by underestimation of tile flow during these periods. P_{BIAS} values of nitrate load results were ~~11~~ 27 % and ~~31~~ 6 % from Rev.528 during the calibration and validation ~~periods~~, and ~~17~~ 31 % and ~~37~~ 23 % from Rev.615 during the calibration and validation ~~periods~~, indicating fairly accurate model simulation. Generally, R^2, NSE, MSE and KGE values for simulated nitrate load were satisfactory (> 0.5). However, NSE (0.~~33~~43) and MSE (0.~~40~~41) from Rev.528 during the ~~the~~ calibration ~~period~~ were unsatisfactory, and ~~KGE~~MSE (0.~~48~~49) from Rev.615 during the ~~the validation~~ calibration ~~period~~ were slightly under the acceptable limit (Table 4).

Limitations of this work include limited observed rainfall data for site R5, water table depth calculation after long dry periods, and difficulty in simulating surface runoff, sediment, and nitrate in surface runoff from this extensively tile drained, mildly-sloped watershed. Observed rainfall data for site R5 was from the closest rain gauge station located 6 km southeast of site R5, which may impact the accuracy of flow simulation. There is an opportunity to improve the representation of tile drainage systems in SWAT, especially for individual tiles, and improve Rev.645 functionality at watershed scales.

4 Conclusions

In this study, the old tile drainage routine in SWAT2009 (Rev.528) and the new tile drainage routine in SWAT2012 (Rev.615 and Rev.645) were used to simulate monthly tile flow, nitrate in tile flow, surface runoff, and sediment and nitrate in surface runoff at field sites, and monthly flow, sediment and nitrate in flow at a river station. Performance of both the old and new r~~r~~outines was evaluated and compared with observed values.

The results showed that Rev.615 satisfactorily simulated corn and soybean yields at field sites, and both the old and new routines provided satisfactory tile flow and nitrate in tile flow results at subsurface sites, satisfactory flow and nitrate load in flow, and reasonable sediment load in flow results at the river station after model calibration. Rev.645 with an improved curve number calculation method provided satisfactory surface runoff, and reasonable sediment and nitrate load in surface runoff results at surface stations.

Generally, simulated tile flow results for the old routine from Rev.528 were better than those for the new routine from Rev.615 at ~~site B~~the subsurface station with random pattern tile, while simulated tile flow results from the new routine were better than those from the old routine at ~~site E~~the subsurface station with constant tile spacing. Nitrate in tile flow results from the new routine from Rev.615 were better than those from the old routine from Rev.528 at both sites. Simulated flow and nitrate in flow results from the new routine were better than those from the old routine at ~~site R5~~the river station on the county line. The new routine provided more realistic and accurate simulation of tile drainage, and the new curve number retention parameter adjustment factor in Rev.645 improved surface runoff simulation, and is suitable for surface runoff simulation in mildly-sloped watersheds.

The results determined which tile drainage routine can provide a better model fit, and provided representative parameter sets in SWAT for simulation of tile flow, nitrate in tile flow, surface runoff, sediment and nitrate in surface runoff at field scale, and simulation of streamflow, and sediment and nitrate in streamflow at watershed scale in tile-drained watersheds. The results provide guidance for selection of tile drainage routines and related parameter sets for accurate simulation of tile drainage systems for hydrologic processes ~~tile drainage simulation~~ at both field and watershed scales, and can be used for tile flow, runoff, and sediment and nitrate losses simulation of mildly-sloped watersheds in the Midwest US. It is necessary and important to test tile drainage routines and related parameter sets before their applications in hydrological and water quality modeling. To improve representation of tile drainage system in the model, DEP_IMP can be separated to two parameters, depth to impervious layer and soil permeability factor. Water table depth calculation during long dry periods can also be improved. The new routine and the improved curve number calculation method can be tested for more individual tiles and watersheds.

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References

Algoazany, A., Kalita, P., Czapar, G., and Mitchell, J.: Phosphorus transport through subsurface drainage and surface runoff from a flat watershed in east central Illinois, USA, J. Environ. Qual., 36, 681-693, doi:10.2134/jeq2006.0161, 2007.

Arnold, J., Gassman, P., King, K., Saleh, A., and Sunday, U.: Validation of the subsurface tile flow component in the SWAT model, Trans. ASAE, 99-2138, 1999.

Basheer, A. K., Lu, H., Omer, A., Ali, A. B., and Abdelgader, A. M. S.: Impacts of climate change under CMIP5 RCP scenarios on the streamflow in the Dinder River and ecosystem habitats in Dinder National Park, Sudan, Hydrol. Earth Syst. Sci., 20, 1331-1353, doi:10.5194/hess-20-1331-2016, 2016.

Boles, C. M., Frankenberger, J. R., and Moriasi, D. N.: Tile Drainage Simulation in SWAT2012: Parameterization and Evaluation in an Indiana Watershed, Trans. ASABE, 58, 1201-1213, doi: 10.13031/trans.58.10589, 2015.

Cibin, R., Trybula, E., Chaubey, I., Brouder, S. M., and Volenec, J. J.: Watershed-scale impacts of bioenergy crops on hydrology and water quality using improved SWAT model, GCB Bioenergy, doi: 10.1111/gcbb.12307, 2016.

Cooperative Extension Service: Iowa Drainage Guide. Special Report (Revised). Ames, IA: Iowa State University, Cooperative Extension Service., 1987.

Cuadra, P., and Vidon, P.: Storm nitrogen dynamics in tile-drain flow in the US Midwest, Biogeochemistry, 104, 293-308, 2011.

Diaz, R. J., and Solow, A.: Ecological and economic consequences of hypoxia: topic 2 report for the integrated assessment on hypoxia in the Gulf of Mexico, 1999.

Drablos, C., Konyha, K., Simmons, F., and Hirschi, M.: Estimating soil parameters used in drainmod for artificialy drained soils in Illinois, Trans. ASAE, 1988.

Du, B., Arnold, J., Saleh, A., and Jaynes, D.: Development and application of SWAT to landscapes with tiles and potholes, Trans. ASAE, 48, 1121-1133, doi: 10.13031/2013.18522, 2005.

Du, B., Saleh, A., Jaynes, D., and Arnold, J.: Evaluation of SWAT in simulating nitrate nitrogen and atrazine fates in a watershed with tiles and potholes, Trans. ASABE, 49, 949-959, doi: 10.13031/2013.21746, 2006.

Edwards, J. T., and Purcell, L. C.: Soybean yield and biomass responses to increasing plant population among diverse maturity groups, Crop Sci., 45, 1770-1777, doi:10.2135/cropsci2004.0564, 2005.

Edwards, J. T., Purcell, L. C., and Vories, E. D.: Light interception and yield potential of short-season maize (L.) hybrids in the Midsouth, Agron. J., 97, 225-234, doi:10.2134/agronj2005.0225, 2005.

Guo, T., He, B., Jiang, X., Ma, Y., Wu, Y., Xiang, M., Chen, Y., and Tang, C.: Effect of Leucaena leucocephala on soil organic carbon conservation on slope in the purple soil area, Acta Ecol. Sin./Shengtai Xuebao, 32, 190-197, doi:10.5846/stxb201011261684, 2012a.

Guo, T., He, B. H., and Chen, J. J.: Study on SOC Forecast Model in Regions of Hilly Purple Soil by Water Erosion, Adv. Mater. Res., 391, 982-987, doi:10.4028/www.scientific.net/AMR.391-392.982, 2012b.

Guo, T., Engel, B. A., Shao, G., Arnold, J. G., Srinivasan, R., and Kiniry, J. R.: Functional Approach to Simulating Short-Rotation Woody Crops in Process-Based Models, BioEnergy Res., 8, 1598-1613, doi:10.1007/s12155-015-9615-0, 2015.

Guo, T., Cibin, R., Chaubey, I., Gitau, M., Arnold, J. G., Srinivasan, R., Kiniry, J. R., and Engel, B. A.: Evaluation of bioenergy crop growth and the impacts of bioenergy crops on streamflow, tile drain flow and nutrient losses in an extensively tile-drained watershed using SWAT, Sci. Total Environ., 613–614, 724-735, https://doi.org/10.1016/j.scitotenv.2017.09.148, 2018.

Gupta, H. V., Sorooshian, S., and Yapo, P. O.: Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration, J. Hydrol. Eng., 4, 135-143, doi:10.1061/(ASCE)1084-0699(1999)4:2(135), 1999.

Jaynes, D., and James, D.: The extent of farm drainage in the United States, US Department of Agriculture, 2007.

Jha, M. K.: Evaluating hydrologic response of an agricultural watershed for watershed analysis, Water, 3, 604-617, 2011.

Kalita, P., Algoazany, A., Mitchell, J., Cooke, R., and Hirschi, M.: Subsurface water quality from a flat tile-drained watershed in Illinois, USA, Agric., Ecosyst. Environ., 115, 183-193, doi:10.1016/j.agee.2006.01.006, 2006.

Keefer, L.: Sediment and Water Quality Monitoring for the Vermilion River and Little Vermilion River Watersheds, Illinois State Water Survey, 2003.

Kiniry, J., Landivar, J., Witt, M., Gerik, T., Cavero, J., and Wade, L.: Radiation-use efficiency response to vapor pressure deficit for maize and sorghum, Field Crops Res., 56, 265-270, doi:10.1016/S0378-4290(97)00092-0, 1998.

Kirkham, D.: Theory of land drainage. Drainage of Agricultural Lands, Agron. Monogr. ASA, Madison, WI, 1957.

Koch, S., Bauwe, A., and Lennartz, B.: Application of the SWAT model for a tile-drained lowland catchment in North-Eastern Germany on subbasin scale, Water Resour. Manage., 27, 791-805, doi:10.1007/s11269-012-0215-x, 2013.

Krause, P., Boyle, D., and Bäse, F.: Comparison of different efficiency criteria for hydrological model assessment, Adv. Geosci., 5, 89-97, 2005.

Lal, R., Logan, T., and Fausey, N.: Long-term tillage and wheel traffic effects on a poorly drained mollic ochraqualf in northwest Ohio. 1. Soil physical properties, root distribution and grain yield of corn and soybean, Soil Tillage Res., 14, 341-358, doi:10.1016/0167-1987(89)90054-8, 1989.

Larose, M., Heathman, G., Norton, L., and Engel, B.: Hydrologic and atrazine simulation of the Cedar Creek watershed using the SWAT model, J. Environ. Qual., 36, 521-531, doi:10.2134/jeq2006.0154, 2007.

Lindquist, J. L., Arkebauer, T. J., Walters, D. T., Cassman, K. G., and Dobermann, A.: Maize radiation use efficiency under optimal growth conditions, Agron. J., 97, 72-78, doi:10.2134/agronj2005.0072, 2005.

Luo, Y., Arnold, J., Allen, P., and Chen, X.: Baseflow simulation using SWAT model in an inland river basin in Tianshan Mountains, Northwest China, Hydrol. Earth Syst. Sci., 16, 1259-1267, doi:10.5194/hess-16-1259-2012, 2012.

Mastrodomenico, A. T., and Purcell, L. C.: Soybean nitrogen fixation and nitrogen remobilization during reproductive development, Crop Sci., 52, 1281-1289, doi:10.2135/cropsci2011.08.0414, 2012.

Mitchell, J., Kalita, P., Hirschi, M., and Cooke, R.: Upland drainage-watershed hydrology is different, AWRA 2003 Spring Specialty Conf. Agricultural Hydrology and Water Quality, 2003, 2003.

Moriasi, D., Arnold, J., and Green, C.: Incorporation of Hooghoudt and Kirkham tile drain equations into SWAT2005, Proc. 4th Intl. SWAT Conf, 2005, 139-147, 2007.

Moriasi, D., Rossi, C., Arnold, J., and Tomer, M.: Evaluating hydrology of the Soil and Water Assessment Tool (SWAT) with new tile drain equations, J Soil Water Conserv., 67, 513-524, doi: 10.2489/jswc.67.6.513, 2012.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L.: Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, Trans. ASABE, 50, 885-900, 2007.

Moriasi, D. N., Gowda, P. H., Arnold, J. G., Mulla, D. J., Ale, S., Steiner, J. L., and Tomer, M. D.: Evaluation of the Hooghoudt and Kirkham tile drain equations in the Soil and Water Assessment Tool to simulate tile flow and nitrate-nitrogen, J. Environ. Qual., 42, 1699-1710, doi:10.2134/jeq2013.01.0018, 2013.

Muhr, J., Höhle, J., Otieno, D. O., and Borken, W.: Manipulative lowering of the water table during summer does not affect CO2 emissions and uptake in a fen in Germany, Ecol. Appl., 21, 391-401, doi:10.1890/09-1251.1, 2011.

Nash, J. E., and Sutcliffe, J. V.: River flow forecasting through conceptual models part I—A discussion of principles, J Hydrol., 10, 282-290, doi:10.1016/0022-1694(70)90255-6, 1970.

Neitsch, S. L., Williams, J., Arnold, J., and Kiniry, J.: Soil andWater Assessment Tool Theoretical Documentation Version 2009, Grassland, Soil andWater Research Laboratory, Agricultural ResearchService and Blackland Research Center, Texas Agricultural Experiment Station, College Station, Texas, 2011.

Qiu, L.-j., Zheng, F.-l., and Yin, R.-s.: SWAT-based runoff and sediment simulation in a small watershed, the loessial hilly-gullied region of China: capabilities and challenges, International Journal of Sediment Research, 27, 226-234, doi:10.1016/S1001-6279(12)60030-4, 2012.

Rabalais, N. N., Turner, R. E., Justic, D., Dortch, Q., and Wiseman Jr, W. J.: Characterization of hypoxia: topic I report for the integrated assessment on hypoxia in the Gulf of Mexico, Silver Spring, MD, Monograph or Serial Issue, 1999.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., and Tarantola, S.: Global sensitivity analysis: the primer, John Wiley & Sons, 2008.

Schilling, K. E., and Helmers, M.: Effects of subsurface drainage tiles on streamflow in Iowa agricultural watersheds: Exploratory hydrograph analysis, Hydrol. Processes, 22, 4497-4506, doi:10.1002/hyp.7052, 2008.

Sexton, A., Shirmohammadi, A., Sadeghi, A., and Montas, H.: Impact of parameter uncertainty on critical SWAT output simulations, Trans. ASABE, 54, 461-471, doi: 10.13031/2013.36449, 2011.

Shope, C. L., Maharjan, G. R., Tenhunen, J., Seo, B., Kim, K., Riley, J., Arnhold, S., Koellner, T., Ok, Y. S., Peiffer, S., Kim, B., Park, J. H., and Huwe, B.: Using the SWAT model to improve process descriptions and define hydrologic partitioning in South Korea, Hydrol. Earth Syst. Sci., 18, 539-557, doi:10.5194/hess-18-539-2014, 2014.

Sinclair, T. R., and Muchow, R. C.: Radiation use efficiency, Adv. Agron., 65, 215-265, doi:10.1016/S0065-2113(08)60914-1, 1999.

Singh, J., Kalita, P., Mitchell, J., Cooke, R., and Hirschi, M.: Simulation of tile flow for a flat tile drained watershed in east central Illinois, 2001 ASAE Annual Meeting, 1, doi: 10.13031/2013.3824, 2001a.

Singh, J., Kalita, P., Mitchell, J., Cooke, R., and Hirschi, M.: Tile water quality predictions using DRAINMOD-N and RZWQM, 2001 ASAE Annual Meeting, 1, doi: 10.13031/2013.3825, 2001b.

Singh, R., Helmers, M., and Qi, Z.: Calibration and validation of DRAINMOD to design subsurface drainage systems for Iowa's tile landscapes, Agric. Water Manage., 85, 221-232, doi:10.1016/j.agwat.2006.05.013, 2006.

Singh, R., Helmers, M., Crumpton, W., and Lemke, D.: Predicting effects of drainage water management in Iowa's subsurface drained landscapes, Agric. Water Manage., 92, 162-170, doi:10.1016/j.agwat.2007.05.012, 2007.

Singh, R., and Helmers, M. J.: Improving Crop Growth Simulation in the Hydrologic Model DRAINMOD to Simulate Corn Yields in Subsurface Drained Landscapes, 2008 Providence, Rhode Island, June 29–July 2, 2008, 1, doi:10.13031/2013.24598, 2008.

Skaggs, R. W., Youssef, M., and Chescheir, G.: DRAINMOD: Model use, calibration, and validation, Trans. ASABE, 55, 1509-1522, doi: 10.13031/2013.42259, 2012.

Sugg, Z.: Assessing US farm drainage: Can GIS lead to better estimates of subsurface drainage extent, World Resources Institute, Washington, DC, 2007.

Sui, Y., and Frankenberger, J.: Nitrate loss from subsurface drains in an agricultural watershed using SWAT2005, Trans. ASABE, 51, 1263-1272, doi: 10.13031/2013.25243, 2008.

Teshager, A. D., Gassman, P. W., Schoof, J. T., and Secchi, S.: Assessment of impacts of agricultural and climate change scenarios on watershed water quantity and quality, and crop production, Hydrol. Earth Syst. Sci., 20, 3325-3342, doi:10.5194/hess-20-3325-2016, 2016.

Tiemeyer, B., Lennartz, B., and Kahle, P.: Analysing nitrate losses from an artificially drained lowland catchment (North-Eastern Germany) with a mixing model, Agric., Ecosyst. Environ., 123, 125-136, doi:10.1016/j.agee.2007.05.006, 2008.

Van Liew, M., Arnold, J., and Garbrecht, J.: Hydrologic simulation on agricultural watersheds: Choosing between two models, Trans. ASAE, 46, 1539, doi: 10.13031/2013.15643, 2003.

Wang, G., Jager, H. I., Baskaran, L. M., Baker, T. F., and Brandt, C. C.: SWAT Modeling of Water Quantity and Quality in the Tennessee River Basin: Spatiotemporal Calibration and Validation, Hydrol. Earth Syst. Sci. Discuss., 2016, 1-33, doi:10.5194/hess-2016-34, 2016.

Yin, J., He, F., Xiong, Y., and Qiu, G.: Effect of land use/land cover and climate changes on surface runoff in a semi-humid and semi-arid transition zone in Northwest China, Hydrol. Earth Syst. Sci. Discuss., 2016, 1-23, doi:10.5194/hess-2016-212, 2016.

Yuan, Y., Mitchell, J., Walker, S., Hirschi, M., and Cooke, R.: Atrazine losses from corn fields in the Little Vermilion River watershed in east central Illinois, Appl. Eng. Agric., 16, 51, doi: 10.13031/2013.4990, 2000.

Zanardo, S., Basu, N., Botter, G., Rinaldo, A., and Rao, P.: Dominant controls on pesticide transport from tile to catchment scale: Lessons from a minimalist model, Water Resour. Res., 48, doi:10.1029/2010WR010088, 2012.

Figure captions:

Fig. 1. **Schematic of the LVR watershed with location of m~~M~~onitored subsurface, surface and river stations~~ in the LVR watershed~~.**

Fig. 2. **Calibration and validation results for annual crop yields at sites B (a and b)~~,~~ and E (c and d). ~~monthly tile flow (c and d) and nitrate-nitrogen losses in tile flow (e and f) at site B.~~ Obs and ~~, Prcp, Rev528,~~ Rev615 ~~and Rev645~~ represent Observed and~~, Precipitation, Revision 528,~~ Revision 615~~ and Revision 645~~, respectively.**

Fig. 3. **Calibration and validation results for ~~annual crop yields (a and b), and~~ monthly tile flow at sites B (c and d) and E (c and d), and monthly flow at site R5 (e and f). ~~nitrate-nitrogen losses in tile flow (e and f) at site E.~~ Obs, Prcp, Rev528, Rev615 and Rev645 represent Observed, Precipitation, Revision 528, Revision 615 and Revision 645, respectively.**

Fig. 4. **Calibration and validation results for monthly surface runoff at sites Bs (a and b) and Es (c and d).~~, sediment (c and d) and nitrate-nitrogen losses in surface runoff (e and f) at site Bs.~~ Obs, Rev615 and Rev645 represent Observed, Revision 615 and Revision 645, respectively.**

Fig. 5. **Calibration and validation results for monthly ~~surface runoff (a and b),~~ sediment losses in surface runoff at sites Bs (a and b) and Es (c and d), and monthly sediment losses in flow at site R5 (e and f). Obs, Rev528, Rev615 and Rev645 represent Observed, Revision 528, Revision 615 and Revision 645, respectively.**

~~nitrate-nitrogen losses in surface runoff (e and f) at site Es. Obs, Rev615 and Rev645 represent Observed, Revision 615 and Revision 645, respectively.~~

Fig. 6. **Calibration and validation results for monthly nitrate-nitrogen losses in tile flow at sites B (a and b) and E (c and d), and monthly ~~flow (a and b), sediment (c and d) and~~ nitrate-nitrogen losses in flow ~~(e and f)~~ at site R5 (e and f). Obs, ~~Prcp,~~ Rev528, and Rev615 represent Observed, ~~Precipitation,~~ Revision 528 and Revision 615, respectively.**

Fig. 7. **Calibration and validation results for monthly nitrate-nitrogen losses in surface runoff at sites Bs (a and b) and Es (ce and d~~f) at site Es~~. Obs~~, Rev615~~ and Rev645 represent Observed ,~~, Revision 615~~ and Revision 645, respectively.**

Table 1 Monitored subsurface, surface and river stations and data for simulation in the LVR watershed, and cropping and tillage practices for sites B and E

Monitored subsurface, surface and river stations

Site	Soils	Station	Drainage system	Cropping
B	Drummer silt clay loam	Subsurface	Random tile drainage tubing systems in depressional areas	Reduced-Tillage Beans-Corn
Bs	Flanagan silt loam	Surface		
E	Sabina silt loam	Subsurface	Complete tile drainage system at 28 m spacing	No-Tillage Corn-Beans
Es	Xenia silt loam	Surface		
R5	-	River	Random tile systems	-

Data for tile drainage simulation

Data type	Source	Format	Date
Elevation	[1]USGS The National Map Viewer	30m raster	
[2]SSURGO	[4]USDA Web Soil Survey	Polygon Shapefile	
[3]LULC	[1]USGS The National Map Viewer	Raster	2006
Temperature, solar radiation, relative humidity and wind speed	[5]ISWS	Tabular data	1991 - 2003
Precipitation	[6]UIUC	Tabular data	1991 - 2003
Corn and soybean yield, planting, harvest, fertilization and tillage for sites B and E	[6]UIUC	Tabular data	1991- 2003
Tile flow, nitrate-nitrogen in tile flow, site B	[6]UIUC		1992 – 2003*
Tile flow, nitrate-nitrogen in tile flow, site E	[6]UIUC		1991 - 2002
Surface runoff, sediment and nitrate-nitrogen in runoff for sites Bs and Es	[6]UIUC		1993 - 2003
Flow, sediment and nitrate-nitrogen in flow for site R5	[6]UIUC		1993 - 2003

Cropping and tillage practices for sites B and E

Year	Crop		Planting date (Month/day)		Harvest date (Month/day)		Tillage type	
Site	B	E	B	E	B	E	B	E
1991	Soybean	Corn	05/08	09/21	09/21	10/08	Reduced tillage-chisel plowed, disked, or field cultivated	No tillage
1992	Corn	Soybean	04/30	10/06	10/06	10/06		
1993	Soybean	Corn	05/17	09/30	09/30	11/08		
1994	Corn	Soybean	04/21	09/13	09/13	10/06		
1995	Soybean	Corn	06/04	10/02	10/02	10/17		
1996	Corn	Soybean	04/18	09/19	09/19	10/17		
1997	Soybean	Corn	04/29	09/26	09/26	10/15		
1998	Corn	Soybean	04/26	09/23	09/23	09/28		
1999	Soybean	Corn	05/07	09/19	09/19	11/09		
2000	Corn	Soybean	04/13	09/19	09/19	10/04		
2001	Soybean	Corn	04/30	09/27	09/27	10/29		
2002	Corn	Soybean	05/21	10/01	10/01	10/01		
2003	Soybean	Corn	05/22	10/01	10/01	10/27		

[1]USGS: U.S. Geological Survey

[2]SSURGO: Soil Survey Geographic Database

[3] LULC: Land Use/Land Cover
[4] USDA: U.S. Department of Agriculture
[5] ISWS: Illinois State Water Survey
[6] UIUC: University of Illinois at Urbana Champaign, USA
* Tile flow data during 2000 for site B was corrupted and was not used in this study.

Table 2 Adjusted parameter values for plant growth simulation, and parameters used for model calibration

Adjusted parameter values for corn and soybean growth simulation

Parameter	Description	Initial value		Adjusted value	
		corn	soybean	corn	soybean
BIO_E	Radiation-use efficiency ((kg ha^{-1})/(MJ m^{-2}))	39	25	36	25
PHU	Potential heat units	1556	1556	1500	1250
T_BASE	Minimum temperature for plant growth (°C)	8	10	8	8
HVSTI	Harvest index for optimal growing conditions	0.50	0.31	0.50	0.40
CPYLD	Normal fraction of phosphorus in yield (kg P kg^{-1} yield)	0.0016	0.0091	0.0016	0.0067

Parameters used for various processes during model calibration

Parameter	Description	Process
CN II ~~ICN~~	~~CN method flag: 0 use traditional SWAT method, which bases CN on soil moisture, 1 use method which bases CN on plant ET~~	Surface runoff
~~CN2~~	Soil moisture condition II curve number~~r~~	
~~CNCOEF~~	~~Plant ET curve number coefficient~~	
R2ADJ	Curve number retention parameter adjust factor	
SURLAG	Surface runoff lag coefficient	
TDRAIN	Time to drain soil to field capacity (h)	Tile drains
GDRAIN	Drain tile lag time (h)	
DEP_IMP	Depth to impervious layer (mm)	
LATKSATF	Multiplication factor to determine lateral saturated hydraulic conductivity	
~~SDRAIN~~	~~Tile spacing (mm)~~	
~~SOL_K(1)~~	~~Saturated hydraulic conductivity (mm h^{-1})~~	
ESCO	Soil evaporation compensation factor	Evapotranspiration
ADJ_PKR	Peak rate adjustment factor for sediment routing in the subbasin (tributary channels)	Sediment losses
USLE_C	Minimum value of USLE C factor for water erosion	
SPEXP	Exponent parameter for calculating sediment re-entrained in channel sediment routing	
CH_COV1	Channel erodibility factor	
CMN	Rate factor for mineralization for humus active organic nutrients (N)	Nitrate losses
RCN	Concentration of nitrogen in rainfall (mg N L^{-1})	
NPERCO	Nitrogen concentration reduction coefficient	
SDNCO	Denitrification threshold water content	
CDN	Denitrification exponential rate coefficient	

Table 3 C~~C~~alibrated values of adjusted parameters for tile flow and nitrate-N calibration of SWAT at sites B, E, Bs, Es and R5

Parameter	Range	Calibrated value											
		Site B			Site E			Site Bs		Site Es		Site R5	
		528	615	645	528	615	645	615	645	615	645	528	615
~~ICN~~		~~1~~	~~1~~	~~0~~	~~0~~	~~0~~	~~0~~	~~0~~	~~0~~	~~0~~	~~0~~	~~1~~	~~0~~
CN II~~CN2~~	-0.2~-0.1	61	63	-	64	65	-	60	-	60	-	-0.2	-0.2
~~CNCOEF~~	~~0.5~2~~	~~0.83~~	~~0.98~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~0.58~~	~~-~~
R2ADJ	0.6~0.9~~1~~	-	-	0.8~~96~~0	-	-	0.8~~97~~5	-	0.~~88~~81	-	0.~~81~~83	-	-
SURLAG	0.0~~5~~~2.0	0.3~~1.91~~	0.3~~1.62~~	0.3~~0.97~~	0.2~~0.61~~	0.2~~1.59~~	0.2~~0.73~~	0.3~~1.78~~	0.3~~1.80~~	0.2~~1.82~~	0.2~~1.83~~	0.3~~0.77~~	0.3~~1.03~~
TDRAIN (h)	24~48	26	-	-	25	-	-	-	-	-	-	26	-
GDRAIN (h)	24~48	25	-	-	26	-	-	-	-	-	-	25	-
DEP_IMP (mm)	1200~3600	2765~~3400~~	2800~~2300~~	2800~~2600~~	3000~~2100~~	2900~~1200~~	2900~~1500~~	2850~~3400~~	2765~~2000~~	2950~~3100~~	2950~~1900~~	2800~~3600~~	2800~~2700~~
LATKSATF	0.01~4	-	1~~2~~.2	1.0~~2~~	-	1.0~~0.07~~	1.0~~0.26~~	1.4~~1.68~~	1.4~~0.48~~	1.2~~1.89~~	1.2~~0.28~~	-	1.1~~05~~
~~SDRAIN (mm)~~	~~25000~50000~~	~~-~~	~~33000~~	~~37000~~	~~-~~	~~28000~~	~~28000~~	~~36000~~	~~29000~~	~~29000~~	~~41000~~	~~-~~	~~38000~~
~~SOL_K(1) (mm h^{-1})~~	~~-0.8~0.8~~	~~-0.24~~	~~0.68~~	~~-0.79~~	~~0.32~~	~~-0.62~~	~~0.62~~	~~0.03~~	~~0.52~~	~~-0.17~~	~~0.36~~	~~-0.26~~	~~0.07~~
ESCO	0.80~0.99	0.88~~0.94~~	0.91~~0.95~~	0.91~~0.86~~	0.90~~0.82~~	0.88~~0.88~~	0.91~~0.91~~	0.91~~0.85~~	0.88~~0.85~~	0.90~~0.90~~	0.90~~0.95~~	0.91~~0.93~~	0.90~~0.98~~
~~SFTMP (°C)~~	~~-5~5~~	~~-1.79~~	~~2.77~~	~~-4.47~~	~~-1.99~~	~~1.34~~	~~3.35~~	~~-4.96~~	~~4.37~~	~~4.53~~	~~3.97~~	~~0.58~~	~~-4.25~~
~~SMTMP (°C)~~	~~-5~5~~	~~-2.28~~	~~2.59~~	~~-3.78~~	~~3.39~~	~~0.86~~	~~-1.52~~	~~-1.4~~	~~4.8~~	~~0.11~~	~~1.57~~	~~0.99~~	~~2.08~~
~~GW_DELAY (days)~~	~~10~40~~	~~16~~	~~29~~	~~22~~	~~27~~	~~21~~	~~20~~	~~12~~	~~16~~	~~32~~	~~19~~	~~37~~	~~25~~
~~RCHRG_DP~~	~~0~0.3~~	~~0.05~~	~~0.09~~	~~0.28~~	~~0.04~~	~~0.11~~	~~0.03~~	~~0.08~~	~~0.20~~	~~0.21~~	~~0.28~~	~~0.72~~	~~0.56~~
~~SOL_AWC(1)~~	~~-0.2~0.2~~	~~0.05~~	~~-0.19~~	~~0.18~~	~~0.04~~	~~-0.09~~	~~-0.03~~	~~0.03~~	~~-0.16~~	~~0.19~~	~~0.15~~	~~0.06~~	~~-0.03~~
ADJ_PKR	0.5~2	-	-	-	-	-	-	-	1.2~~75~~	-	1.1~~0.74~~	1.2~~1.10~~	1.2~~1.16~~
USLE_C {19}	-0.25~0.25	-	-	-	-	-	-	-	0.12	-	0.15	0.15	0.15
USLE_C {56}	-0.25~0.25	-	-	-	-	-	-	-	0.05	-	0.06	0.07	0.07
~~HRU_SLP (m m^{-1})~~	~~0~0.02~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~0~~	~~-~~	~~0.02~~	~~0.02~~	~~0~~
~~SLSUBBSN (m)~~	~~-0.1~0.1~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~		~~-~~		~~0.08~~	~~0.03~~

~~USLE_K(1)~~	~~-0.1~0.1~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~-~~	~~0.07~~	~~-~~	~~0.1~~	~~0.1~~	~~-0.06~~
SPEXP	1~2	-	-	-	-	-	-	-		-	-	1.5~~0~~	1.~~94~~5
CH_COV1	0~1	-	-	-	-	-	-	-		-	-	0.3~~8~~	0.3~~1~~
CMN	0.0003 ~0.03	0.02	0.02	-	0.~~000~~~~3~~02	0.02	-	-	0.03~~1~~	-	0.03~~2~~	0.~~00~~03	0.03
RCN (mg N L^{-1})	0~15	9~~11~~	9~~15~~	-	11~~0~~	11	-	-	9~~6~~	-	10~~5~~	9~~11~~	9~~0.1~~
NPERCO	0~1	0.15~~84~~	0.15~~01~~	-	0.12~~53~~	0.~~48~~12	-	-	0.~~99~~12	-	~~1~~0.13	0.~~99~~15	0.~~99~~15
SDNCO	0~1.5	1.1~~25~~	1.1~~26~~	-	1.1~~02~~	1.1~~39~~	-	-	~~1.30~~0.9	-	0.9~~3~~	1.0	1.0~~46~~
CDN	0~1	0.06~~1~~	0.06~~2~~	-	0.~~33~~05	0.~~28~~05	-	-	~~1~~0.06	-	~~1~~0.05	0.06	0.06

Negative value for CN II ~~CN2~~, and value for ~~SOL_K(1), SOL_AWC(1) (mm H_20 mm^{-1} soil), USLE_K(1) (0.013 (metric ton m^2 h)/(m^3 metric ton cm)),~~ USLE_C{19}, and USLE_C{56} is relative change to default value. ~~(1) indicates the first soil layer.~~ {19} and {56} represent corn and soybean, respectively.

Table 4 Performance evaluation of the calibrated and validated results at sites B, E, Bs, Es and R5

	Annual Crop yield (t ha^{-1})		Monthly Tile flow (mm)						Monthly NO3-N in tile flow (kg ha^{-1})			
	Cali	Vali	Cali			Vali			Cali		Vali	
Revision	615	615	528	615	645	528	615	645	528	615	528	615
Site B												
P_{BIAS} (%)	13	2	3	~~14~~3	-~~19~~28	~~4~~21	~~3~~6	-18	~~8~~39	~~33~~24	~~23~~31	~~18~~34
R^2	0.99	0.92	0.~~73~~80	0.~~49~~65	0.~~72~~64	0.~~80~~65	0.~~69~~63	0.~~64~~61	0.~~65~~76	0.~~37~~70	0.~~67~~78	0.~~78~~76
NSE	0.91	0.91	0.~~71~~79	0.~~54~~65	0.~~66~~61	0.~~80~~63	0.~~68~~63	0.~~58~~59	0.~~66~~70	0.~~22~~68	0.~~63~~75	0.~~77~~68
MSE	0.77	0.76	0.~~60~~67	0.~~54~~57	0.~~53~~49	0.~~67~~52	0.~~53~~43	0.~~48~~38	0.~~59~~62	0.~~43~~60	0.~~55~~61	0.~~64~~50
KGE	0.75	0.89	0.~~85~~89	0.~~70~~74	0.~~75~~63	0.~~86~~69	0.~~78~~68	0.~~73~~59	0.~~68~~89	0.~~48~~74	0.~~71~~69	0.~~78~~68
Site E												
P_{BIAS} (%)	-2	5	~~-37~~24	~~-6~~-3	-16~~17~~	~~-10~~49	22~~12~~	9~~-2~~	~~-1~~74	~~26~~28	~~36~~85	29~~20~~
R^2	0.95	0.92	0.~~68~~65	0.50~~1~~	0.58~~6~~	0.~~75~~62	0.55~~52~~	0.~~56~~63	0.~~72~~33	0.60~~1~~	0.~~38~~50	0.56~~5~~
NSE	0.95	0.88	~~-0.77~~0.32	0.50~~5~~	0.53~~54~~	~~-0.2~~0.00	0.48~~5~~	0.~~53~~60	-0.~~09~~06	0.51~~5~~	~~0.21~~-0.29	0.48~~5~~
MSE	0.80	0.71	~~-0.20~~0.22	0.28~~8~~	0.~~27~~28	0.~~04~~03	0.32~~31~~	0.39~~4~~	0.08	0.32~~3~~	~~0.18~~-0.06	0.31~~34~~
KGE	0.95	0.91	~~-0.05~~0.55	0.61	0.71~~71~~	0.~~15~~38	0.~~6~~57~~0~~	0.76~~74~~	~~0.24~~0.00	0.68~~66~~	~~0.45~~-0.17	0.57~~65~~

	Monthly Surface runoff (mm)				Monthly Sediment (t ha^{-1})		Monthly Nitrate in runoff (kg ha^{-1})	
	Cali		Vali		Cali	Vali	Cali	Vali
Revision	615	645	615	645	645		645	
Site Bs								
P_{BIAS} (%)	-~~614~~108	~~-26~~13	-~~475~~143	~~-74~~12	~~-5~~20	~~37~~-77	~~79~~99	~~53~~77
R^2	0.~~23~~70	0.~~88~~81	0.~~76~~59	0.~~80~~70	0.~~96~~38	0.~~13~~97	0~~.14~~	0.~~01~~96
NSE	~~-4.7~~0.49	0.81	-~~5.95~~0.07	0.64	0.~~95~~27	0.~~11~~67	~~0.06~~-0.03	~~-0.32~~0.38
MSE	~~-2.36~~0.25	0.~~48~~66	~~-1.70~~0.09	0.~~41~~49	0.~~74~~54	0.~~48~~52	0.46~~3~~	0.54~~29~~
KGE	-~~5.33~~0.12	0.~~5~~80	-~~4.22~~0.52	0.~~18~~55	0.~~86~~80	0.55~~10~~	~~-0.34~~0.8	~~-0.11~~0.55
Site Es								
P_{BIAS} (%)	-~~107~~135	-25~~18~~	-~~14~~382	~~-99~~28	~~32~~-8	~~22~~86	~~25~~70	~~83~~59
R^2	0.~~71~~55	0.65~~82~~	0.~~55~~92	0.~~48~~84	0.~~79~~04	0.~~11~~56	0~~.33~~	~~0.005~~0.98
NSE	~~0.50~~-0.11	0.50~~82~~	~~-0.85~~0.21	~~-0.28~~0.77	~~0.46~~-0.7	0.10~~08~~	-0.13~~0.27~~	~~-0.07~~0.63
MSE	0.~~28~~07	0.42~~57~~	0.~~01~~46	0.7~~1~~5	0.07~~39~~	0.50~~27~~	0.28~~31~~	~~0.35~~0.63
KGE	-0.44~~10~~	0.64~~78~~	-0.~~67~~11	~~-0.15~~0.56	0.78~~24~~	0.22~~12~~	0.78~~17~~	~~-0.54~~0.22

	Monthly Flow (cms)				Monthly Sediment (t)				Monthly Nitrate (kg)			
	Cali		Vali		Cali		Vali		Cali		Vali	
Revision	528	615	528	615	528	615	528	615	528	615	528	615
Site R5												
P_{BIAS} (%)	-~~36~~16	-~~48~~26	-20~~1~~	-~~11~~37	~~62~~44	~~10~~-55	-1916~~41~~	-~~474~~3004	~~11~~27	~~17~~31	~~31~~6	23~~7~~
R^2	0.~~85~~71	0.~~84~~65	0.91~~68~~	0.~~63~~86	0.43~~27~~	0.40~~5~~	0.96~~31~~	0.95~~76~~	0.59~~6~~	0.63	0.~~70~~80	0.68~~7~~
NSE	0.~~77~~62	0.~~73~~54	0.89~~60~~	0.~~48~~79	0.40~~18~~	~~0.45~~-1.26	-~~1.05~~256.27	-~~9.67~~470.81	0.4~~3~~3	0.58~~61~~	0.~~57~~72	0.65~~8~~
MSE	0.~~50~~38	0.~~43~~30	0.67~~36~~	0.~~26~~51	0.49~~0~~	0.~~46~~18	~~0.07~~-9.22	-1~~.77~~5.02	0.41~~0~~	0.~~50~~49	0.~~51~~71	0.57~~0~~

KGE	0.~~63~~75	0.~~50~~67	0.~~80~~78	0.6~~7~~1	0.28~~00~~~~1~~	~~0.56~~-0.13	-~~0.63~~23.48	-~~4.61~~35.24	0.62~~5~~	0.~~71~~53	0.~~64~~79	0.64~~8~~

Cali and Vali represent calibration and validation, respectively.

Fig. 1

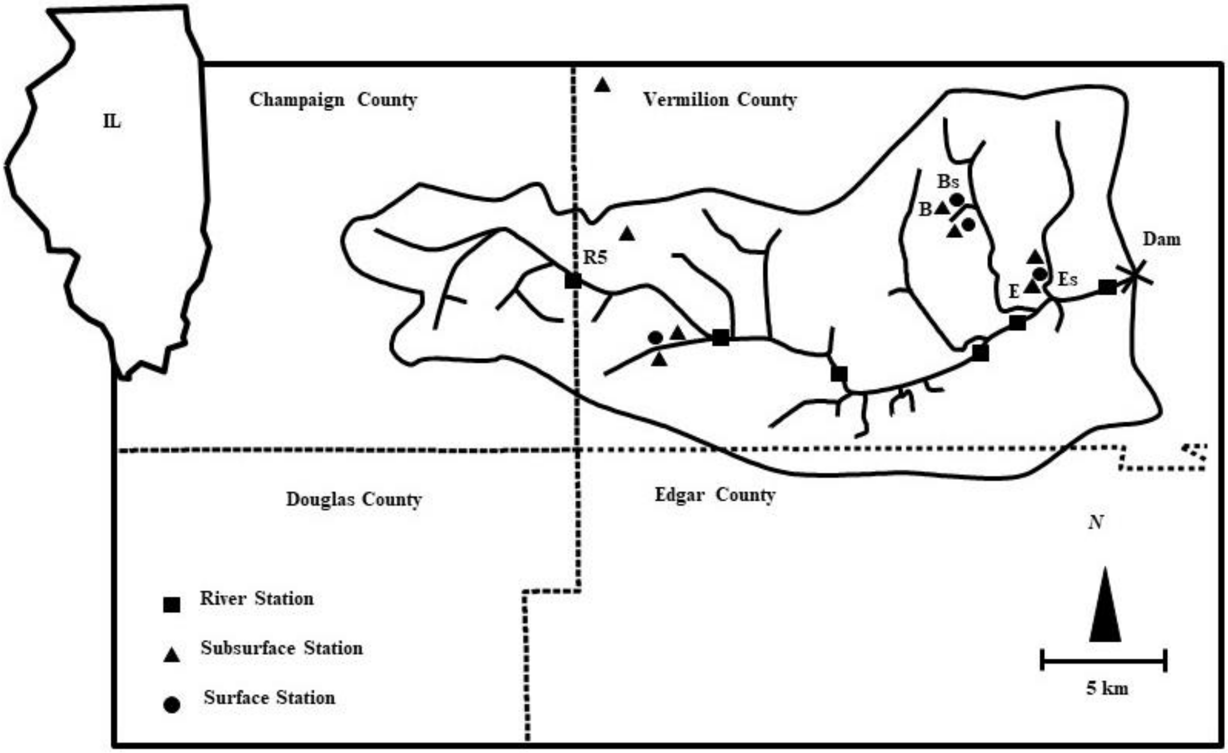


Fig. 2

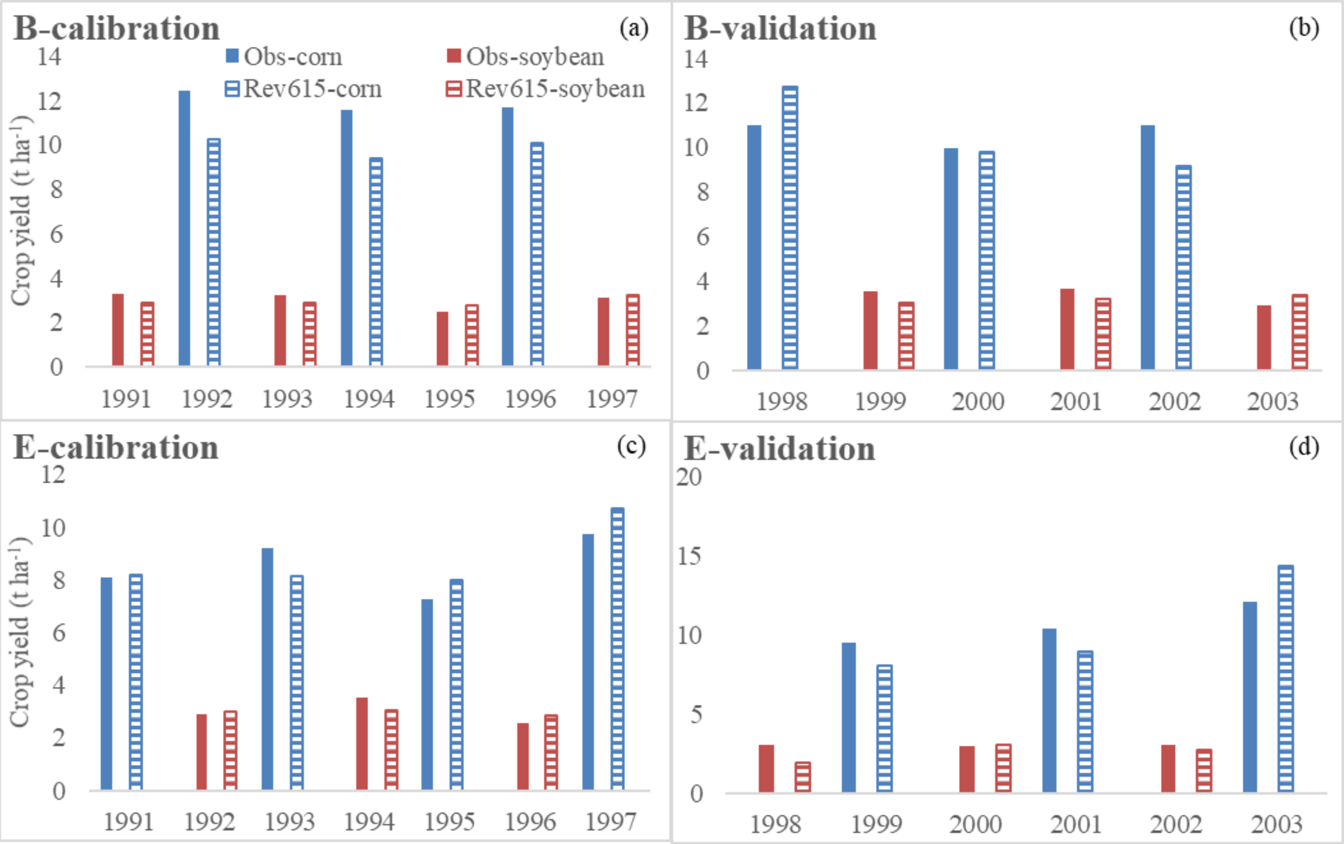

B-calibration
(a)
Obs-corn
Obs-soybean
Rev615-corn
Rev615-soybean
Crop yield (t ha^{-1})
14
12
10
8
6
4
2
0
1991
1992
1993
1994
1995
1996
1997
B-validation
(b)
14
12
10
8
6
4
2
0
1998
1999
2000
2001
2002
2003
E-calibration
(c)
Crop yield (t ha^{-1})
12
10
8
6
4
2
0
1991
1992
1993
1994
1995
1996
1997
E-validation
(d)
20
15
10
5
0
1998
1999
2000
2001
2002
2003

Fig. 3

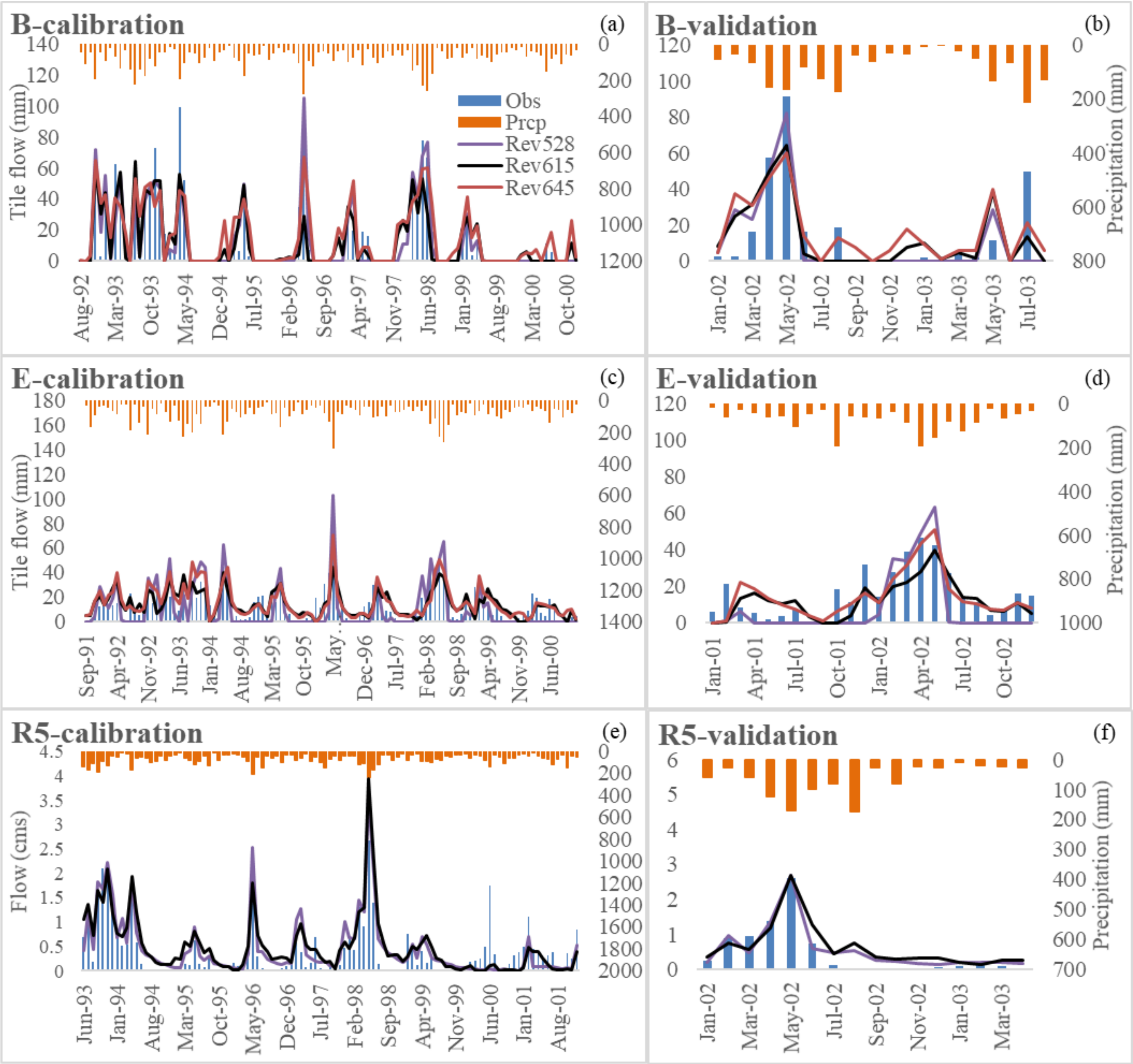

B-calibration
(a)
Tile flow (mm)
140
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
Obs
Prcp
Rev528
Rev615
Rev645
Aug-92
Mar-93
Oct-93
May-94
Dec-94
Jul-95
Feb-96
Sep-96
Apr-97
Nov-97
Jun-98
Jan-99
Aug-99
Mar-00
Oct-00
B-validation
(b)
120
100
80
60
40
20
0
0
200
400
600
800
Precipitation (mm)
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03
May-03
Jul-03
E-calibration
(c)
Tile flow (mm)
180
160
140
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
Sep-91
Apr-92
Nov-92
Jun-93
Jan-94
Aug-94
Mar-95
Oct-95
May…
Dec-96
Jul-97
Feb-98
Sep-98
Apr-99
Nov-99
Jun-00
E-validation
(d)
120
100
80
60
40
20
0
0
200
400
600
800
1000
Precipitation (mm)
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02
R5-calibration
(e)
Flow (cms)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Jun-93
Jan-94
Aug-94
Mar-95
Oct-95
May-96
Dec-96
Jul-97
Feb-98
Sep-98
Apr-99
Nov-99
Jun-00
Jan-01
Aug-01
R5-validation
(f)
6
5
4
3
2
1
0
0
100
200
300
400
500
600
700
Precipitation (mm)
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03

Fig. 4

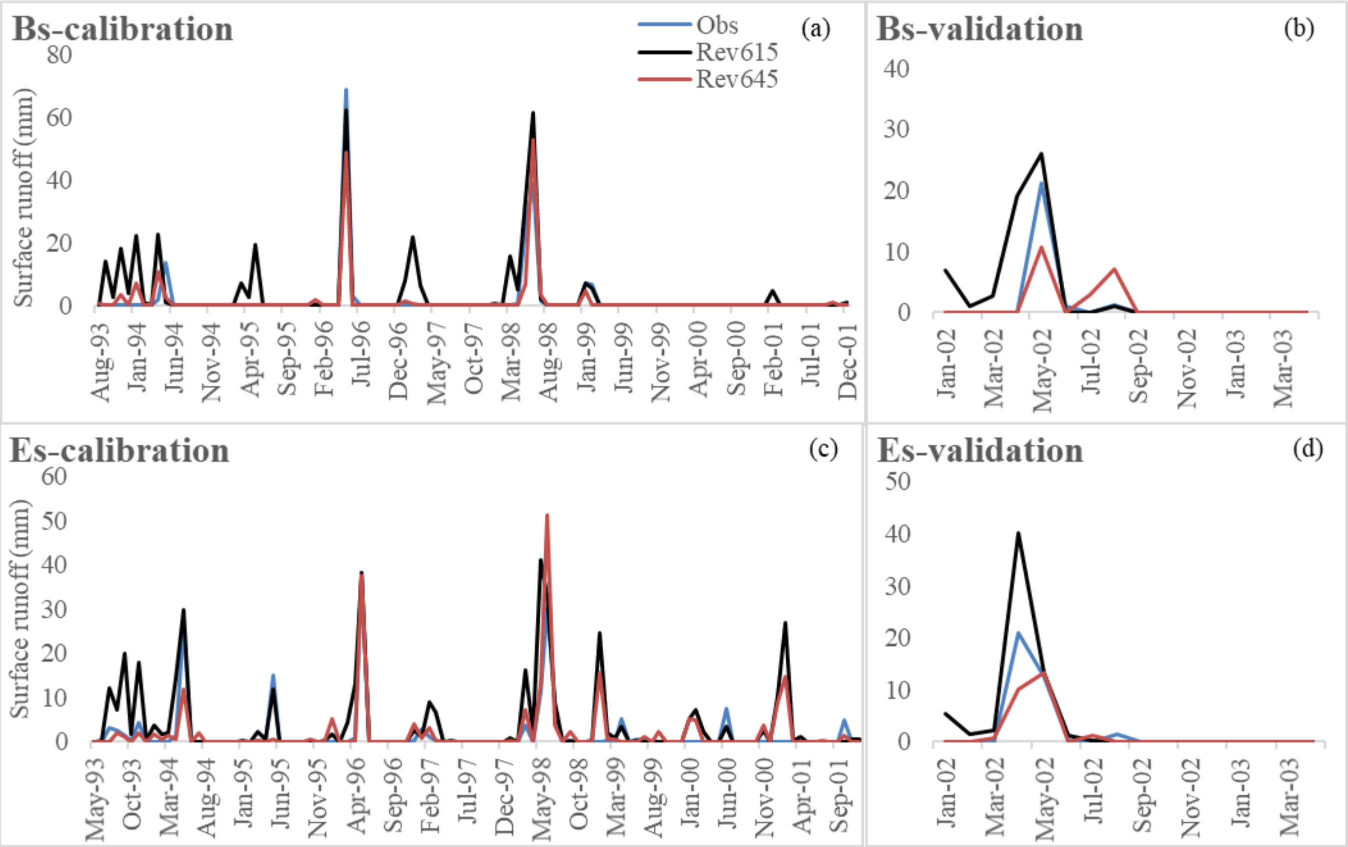

Bs-calibration
(a)
Obs
Rev615
Rev645
Surface runoff (mm)
80
60
40
20
0
Aug-93
Jan-94
Jun-94
Nov-94
Apr-95
Sep-95
Feb-96
Jul-96
Dec-96
May-97
Oct-97
Mar-98
Aug-98
Jan-99
Jun-99
Nov-99
Apr-00
Sep-00
Feb-01
Jul-01
Dec-01
Bs-validation
(b)
40
30
20
10
0
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03
Es-calibration
(c)
Surface runoff (mm)
60
50
40
30
20
10
0
May-93
Oct-93
Mar-94
Aug-94
Jan-95
Jun-95
Nov-95
Apr-96
Sep-96
Feb-97
Jul-97
Dec-97
May-98
Oct-98
Mar-99
Aug-99
Jan-00
Jun-00
Nov-00
Apr-01
Sep-01
Es-validation
(d)
50
40
30
20
10
0
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03

Fig. 5

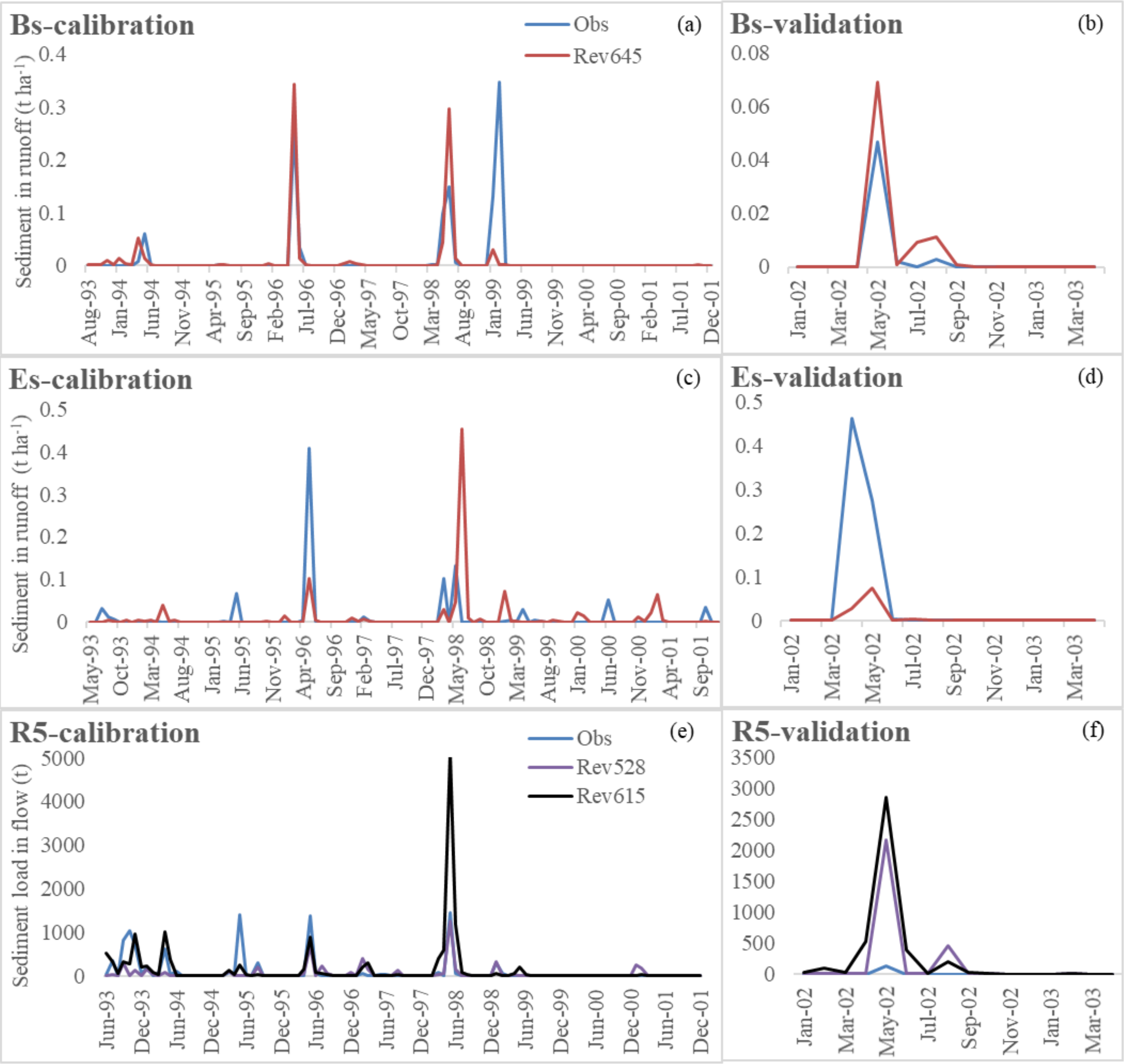

Bs-calibration
(a)
Obs
Rev645
Sediment in runoff (t ha^{-1})
0.4
0.3
0.2
0.1
0
Aug-93
Jan-94
Jun-94
Nov-94
Apr-95
Sep-95
Feb-96
Jul-96
Dec-96
May-97
Oct-97
Mar-98
Aug-98
Jan-99
Jun-99
Nov-99
Apr-00
Sep-00
Feb-01
Jul-01
Dec-01
Bs-validation
(b)
0.08
0.06
0.04
0.02
0
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03
Es-calibration
(c)
Sediment in runoff (t ha^{-1})
0.5
0.4
0.3
0.2
0.1
0
May-93
Oct-93
Mar-94
Aug-94
Jan-95
Jun-95
Nov-95
Apr-96
Sep-96
Feb-97
Jul-97
Dec-97
May-98
Oct-98
Mar-99
Aug-99
Jan-00
Jun-00
Nov-00
Apr-01
Sep-01
Es-validation
(d)
0.5
0.4
0.3
0.2
0.1
0
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03
R5-calibration
(e)
Obs
Rev528
Rev615
Sediment load in flow (t)
5000
4000
3000
2000
1000
0
Jun-93
Dec-93
Jun-94
Dec-94
Jun-95
Dec-95
Jun-96
Dec-96
Jun-97
Dec-97
Jun-98
Dec-98
Jun-99
Dec-99
Jun-00
Dec-00
Jun-01
Dec-01
R5-validation
(f)
3500
3000
2500
2000
1500
1000
500
0
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03

Fig. 6

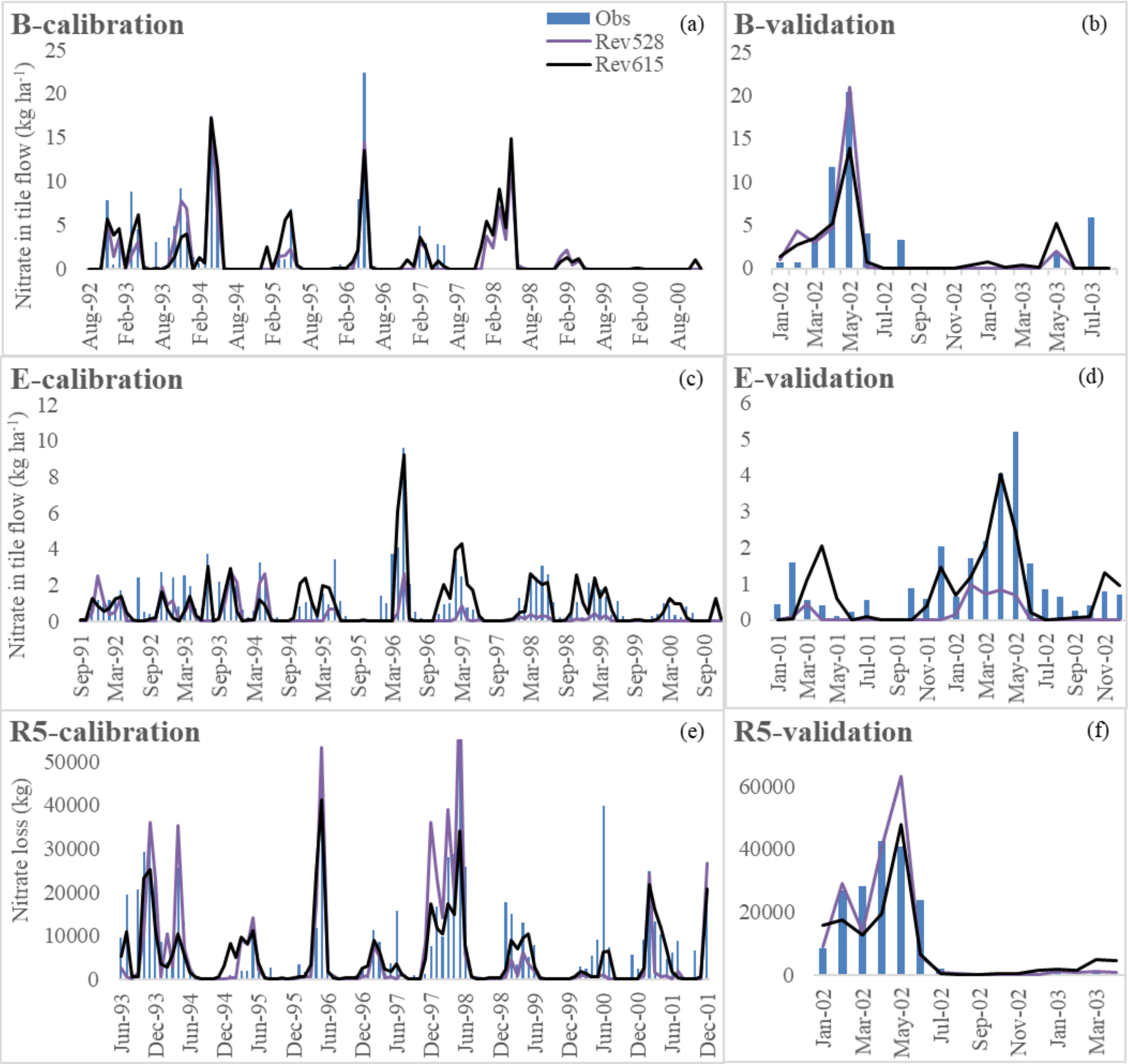
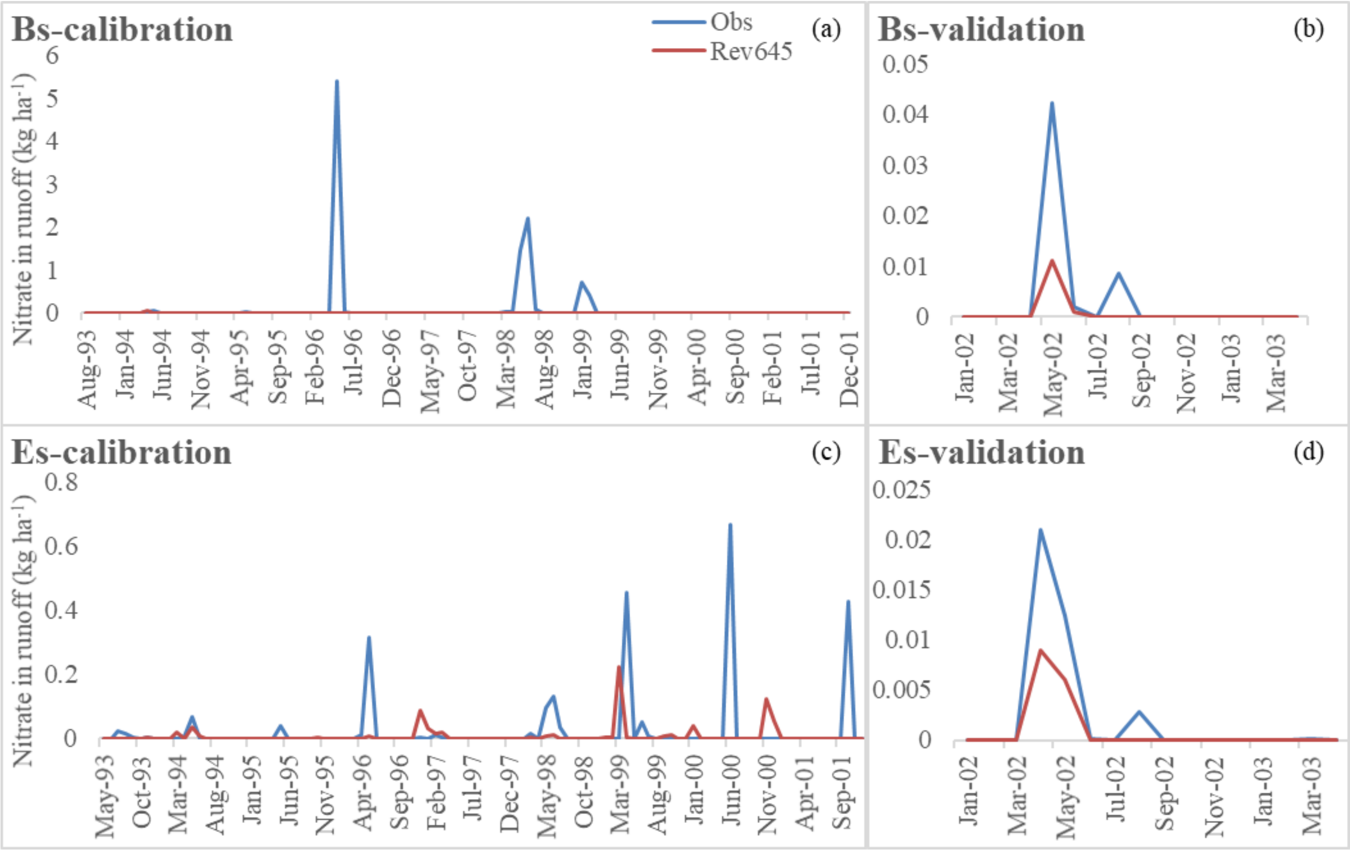

B-calibration
(a)
Obs
Rev528
Rev615
Nitrate in tile flow (kg ha^{-1})
25
20
15
10
5
0
Aug-92
Feb-93
Aug-93
Feb-94
Aug-94
Feb-95
Aug-95
Feb-96
Aug-96
Feb-97
Aug-97
Feb-98
Aug-98
Feb-99
Aug-99
Feb-00
Aug-00
B-validation
(b)
25
20
15
10
5
0
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03
May-03
Jul-03
E-calibration
(c)
Nitrate in tile flow (kg ha^{-1})
12
10
8
6
4
2
0
Sep-91
Mar-92
Sep-92
Mar-93
Sep-93
Mar-94
Sep-94
Mar-95
Sep-95
Mar-96
Sep-96
Mar-97
Sep-97
Mar-98
Sep-98
Mar-99
Sep-99
Mar-00
Sep-00
E-validation
(d)
6
5
4
3
2
1
0
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
R5-calibration
(e)
Nitrate loss (kg)
50000
40000
30000
20000
10000
0
Jun-93
Dec-93
Jun-94
Dec-94
Jun-95
Dec-95
Jun-96
Dec-96
Jun-97
Dec-97
Jun-98
Dec-98
Jun-99
Dec-99
Jun-00
Dec-00
Jun-01
Dec-01
R5-validation
(f)
60000
40000
20000
0
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03

Fig. 7


Bs-calibration
(a)
Obs
Rev645
Nitrate in runoff (kg ha⁻¹)
0
1
2
3
4
5
6
Aug-93
Jan-94
Jun-94
Nov-94
Apr-95
Sep-95
Feb-96
Jul-96
Dec-96
May-97
Oct-97
Mar-98
Aug-98
Jan-99
Jun-99
Nov-99
Apr-00
Sep-00
Feb-01
Jul-01
Dec-01
Bs-validation
(b)
0
0.01
0.02
0.03
0.04
0.05
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03
Es-calibration
(c)
Nitrate in runoff (kg ha⁻¹)
0
0.2
0.4
0.6
0.8
May-93
Oct-93
Mar-94
Aug-94
Jan-95
Jun-95
Nov-95
Apr-96
Sep-96
Feb-97
Jul-97
Dec-97
May-98
Oct-98
Mar-99
Aug-99
Jan-00
Jun-00
Nov-00
Apr-01
Sep-01
Es-validation
(d)
0
0.005
0.01
0.015
0.02
0.025
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03