THE DEVELOPMENT OF SWAT MODELLING SYSTEMS FOR LARGE CORN BELT RIVER BASINS PART 2: MODEL PERFORMANCE AND EVALUATION

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EXTENDED ABSTRACT

Agricultural nonpoint source pollution is the main source of Nitrogen and Phosphorus in the intensely row-cropped Upper Mississippi River Basin (UMRB) and Ohio-Tennessee River Basin (OTRB) stream systems, and is considered the primary cause of the Northern Gulf of Mexico hypoxic zone according to the US Environmental Protection Agency. Thus, this region mostly located in the Midwestern USA, provides a natural location for research on how intensive agriculture for food, feed and biofuel production can coexist with a healthy environment. The use of a process-based hydrologic and water quality model is considered indispensable to address this objective at such a large spatial scale. An integrated modeling system has been constructed with the hydrologic Soil and Water Assessment Tool (SWAT) model (see Part 1 paper describing overall modeling system), capable of estimating river basin responses to alternative cropping and/or management strategies. To facilitate the identification of optimum locations for a cost-effective river basin management, this SWAT large-scale application incorporates a greatly refined subwatershed structure based on the 12-digit hydrologic units (subwatersheds), while the land phase of the hydrologic and nutrient cycles are calculated at thousands of Hydrologic Response Units, which represent unique combinations of land, soil and topographical features. However, given the very large scale and the need to ensure the reliability of flow and pollutant load predictions at various locations within such hydrologic systems, a model’s calibration becomes a time-demanding and challenging task. The purpose of the current article is to demonstrate a semi-automatic calibration approach for large-scale and spatially detailed modeling studies, with the use of the Sequential Uncertainty Fitting algorithm (SUFI-2) and the SWAT-CUP interface developed exclusively for SWAT hydrologic projects. The calibration framework provides estimates of the uncertainty of predictions at various locations and can be finalized within a reasonable timeframe with a powerful personal computer (PC). This study presents the whole calibration approach providing guidance on similar efforts at the regional scale.

Keywords: calibration; model predictions; nonpoint source pollution; nitrogen; OTRB; phosphorus; river basin management; SWAT; UMRB.

1. INTRODUCTION

Over-enrichment of nutrients constitutes a major problem in many streams and rivers in the USA, which, in addition to local effects, causes excessive transport of nutrients and eutrophication to downstream lakes, bays and estuaries, and is primarily responsible for
the hypoxia in the Gulf of Mexico (USEPA, 2000). Under recommendations of the Clean Water Action Plan in 1998, the United States Environmental Protection Agency (USEPA) developed a national strategy for establishing water body-specific nutrient criteria for all water bodies (USEPA, 1998) to reduce nutrient concentrations and improve the beneficial ecological uses of surface waters. In addition, the Mississippi River / Gulf of Mexico Watershed Nutrient Task Force (2008) established a goal to reduce the size of the hypoxic zone in the Gulf of Mexico to 5,000 km², which will require substantial reductions in nutrient loadings from the Mississippi/Atchafalaya River basin (MARB) and especially from its most upstream and intensively cultivated parts, the Upper Mississippi River Basin (UMRB) and Ohio-Tennessee River Basin (OTRB), which form the ‘Corn Belt’ Region of the US. Within this large area, trade-offs between the interdependent goals of sustainable biofuel production, food production, and water resources can have significant implications for commodity groups, individual producers and the community as a whole.

Within this context, the appropriate use of physically-based hydrological models for the evaluation of agricultural management scenarios with socio-economic and environmental impacts is rendered crucial. In order to reliably address what-if scenarios, however, extensive calibration of these models at multiple locations would be necessary, based on measured data. The required efforts in developing and validating these models become even more challenging at the regional scale, as data availability at a high resolution and huge input data do not only require a long execution time but also high computation resources. Although calibration and validation guidelines are increasingly developed to facilitate the use of such models (Moriais et al., 2012), manual calibration of a distributed watershed model such as the Soil and Water Assessment Tool (SWAT) is almost infeasible in many large-scale applications (Arnold et al., 2012).

To date, SWAT has already been applied in both UMRB and OTRB to evaluate the effect of cropping systems, conservation practices or climate change on water resources (Jha et al., 2006; Santhi et al., 2009; 2012, Secchi et al., 2011). To maintain the feasibility of a manual calibration, the development of the existing SWAT models was based on the 8-digit watershed or Hydrologic Unit Codes (HUCs) delineation. As the meteorological information in SWAT is assigned at the subbasin level, most of these models were built with climate adjustments for each 8-digit watershed from a combination of point measurements lying within each one of them. A great improvement in capturing meteorological information, which is the major driving force of hydrological processes, would be the use of more refined 12-digit subwatersheds, as described in the Part 1 paper by Gassman et al. (2013). Such a fine discretization, however, requires more computation resources to calibrate a regional model because each 8-digit watershed contains approximately 40 to 50 12-digit watersheds.

The purpose of this study is to demonstrate a semi-automatic calibration approach for such large-scale and spatially detailed modelling studies, which could be finalized within a reasonable timeframe. The study assesses the performance of SWAT to represent the baseline so that it can then be used for nutrient reduction practices recommended under the USEPA’s policy framework for managing N and P pollution.

2. METHODS AND TOOLS

2.1. SWAT and SWAT-CUP
The Soil and Water Assessment Tool (SWAT) is a river basin model developed by the USDA Agricultural Research Service (Neitsch et al., 2009). The present study used the SWAT2009 version and corresponding ArcSWAT interface. SWAT divides the basin into subbasins and subsequently into Hydrologic Response Units (HRUs), which represent the different combinations of land use, soil types and slope classes in each subbasin. The
processes associated with water and sediment movement, crop growth and nutrient cycling are modelled at the HRU scale and both runoff and pollutants from HRUs are aggregated at the subbasin level and routed downstream. The model is thoroughly described in the SWAT theoretical documentation (Neitsch et al., 2009). This section focuses on SWAT-CUP software developed exclusively for calibrating SWAT projects as well as on the Sequential Uncertainty Fitting (SUFI-2) algorithm, which was selected for the auto-calibration and uncertainty analysis of the UMRB and OTRB models.

SWAT-CUP is a software package with a generic interface, where any sensitivity or calibration/uncertainty program can easily be linked to SWAT by manipulating the large number of text files each project consists of. SWAT-CUP offers a semi-automatic or combined manual/automatic calibration of SWAT projects, allowing the user to control the range of parameter perturbations and seeking to accurately identify their optimum values. Parameters can range either by percentage from their initial values or within predefined lower and upper bounds. From the algorithms included in the SWAT-CUP package No 4 (Abbaspour, 2011), the most efficient is the SUFI-2 algorithm (Abbaspour et al. 2007). SUFI-2 has been successfully used for regional auto-calibration of very large areas such as a whole continent (Schuol et al., 2008a; b) and is highly recommended for the calibration of SWAT models (Arnold et al., 2012).

In SUFI-2, the degree to which all uncertainties are accounted for in the simulation is quantified by a measure referred to as the p-factor, which is the percentage of measured data (flows, sediments, nutrients) bracketed by the 95% prediction uncertainty (95ppu). This is calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through Latin hypercube sampling, disallowing 5% of the very bad simulations. The maximum value for the p-factor is 1 (100%), and ideally all measured data should be bracketed, except the outliers. The second measure quantifying the strength of a calibration/uncertainty analysis in SUFI-2 is the r-factor, which is the average thickness of the 95ppu band divided by the standard deviation of the measured data. The r-factor represents the width of the uncertainty interval or the ‘degree of uncertainty’, which should be as small as possible (Abbaspour, 2011).

2.2. Study areas and models setup
The upper Mississippi River Basin (UMRB) is a headwater basin of the Mississippi River and extends from Lake Itasca in Minnesota to an area just north of Cairo, Illinois above the confluence with the Ohio River, flowing through a 2,100 km waterway (Srinivasan et al., 2010). It covers approximately 492,000 km², including large parts of Illinois, Iowa, Minnesota, Missouri, and Wisconsin as shown in Figure 1. The area is also referred to as Region 07 by the USGS at a 2-digit watershed scale. The region is comprised of 131 USGS delineated 8-digit watersheds and 5,729 12-digit subwatersheds (for a comprehensive comparison see Gassman et al. (2013)). The average annual rainfall within the last 4 decades was 900 mm, ranging from 600 to 1200 mm across the basin. Cropland consists mainly of corn-soybean rotations and occupies 50% of the total UMRB area with 75% of the land being under gentle slopes (the row crop area is inflated somewhat at present, which will be corrected in the next phases of the modeling system development). The mean annual flow of UMRB is 3500 m³/s. The Ohio-Tennessee River Basin (OTRB) consists of two of the six 2-digit water resource regions that make up the Mississippi River drainage: Region 5 (Ohio) and Region 6 (Tennessee). The Ohio River starts in Pennsylvania and ends in Cairo, Illinois, where it flows into the Mississippi River. The Tennessee River joins the Ohio river at Paducah, Kentucky just upstream the confluence of the Ohio and Mississippi. The OTRB covers about 528,000 km² and includes a significant portion of seven states as shown in Figure 1. The region is comprised of 152 USGS delineated 8-digit watersheds and 6,350 12-digit subwatersheds. This basin received a high amount of annual rainfall during the last 40 years, nearly 1200
About half of the land cover in this basin is forested land, 20% cropland and 15% permanent pasture/hay. Corn, soybean and wheat are the major crops grown (Santhi et al., 2012). Compared to the UMRB, the OTRB’s slopes are much steeper, especially all across the forested Tennessee basin. The mean annual flow of OTRB is 8,400 m³/s. Both the UMRB and OTRB contribute 0.5 Gt of TN each to the downstream Mississippi river on a mean annual basis, with about 2/3 of this load occurring as NO₃-N. Phosphorus loads from UMRB and OTRB have been measured at the most downstream USGS stations equal to 30,000 and 48,000 t/y, respectively (USGS online data website: http://waterwatch.usgs.gov/wqwatch/).

The data layers (elevations, land uses and soils) and management information sources used in this work have been described in the Part 1 paper (Gassman et al., 2013). The baseline scenario, representing business as usual for the river basins was modeled with a typical corn-soybean rotation under a typical mulch tillage, which includes 2 tillage practices per year (chisel plow and field cultivator). Both crops are harvested in early October. Fertilizer data are the most important for the parameterization of crop schedules in this SWAT project. We analyzed data of fertilizer and manure at the county level provided from different sources (1 State can have 100 or more counties) and concluded for this phase of the modeling efforts that it would be most appropriate to use aggregated data at the State level for calculating fertilization rates (investigations of more refined

**Figure 1.** The locations of the UMRB and OTRB within the US, and the main tributaries, and dam and monitoring site locations, within each study region.
nutrient application rate assumptions are ongoing). Calculated annual rates of N and P application ranged between 130-200 and 15-30 kg/ha respectively, with N applied only in corn (i.e., every other year). Tile drainage is a common practice for gentle sloping and wet soils in the area; however, no clear record of tile locations and extent of coverage is available. In this study, we used assumptions described in the Part 1 paper which provides % estimates of tile-drained land per county and overlaid it with the GIS layers used in our models. We assigned tiles only in cropland with low slopes in such a way as to respect the total tiled land reported in this study. Finally, we added 60 large reservoirs along the rivers whose water storage volume accounts for more than 60% of the total storage volume of all the existing dams and reservoirs within the study areas.

2.3. Calibration with SUFI-2
The calibration of the UMRB and OTRB models with SUFI-2 in this study was conducted on a monthly basis by using the most recent 14-year period of observed flows (1997-2010 - http://waterwatch.usgs.gov/wqwatch/). To make the process feasible with respect to total time needed for thousands of iterations (SWAT runs), we first created smaller SWAT projects, each one for each of the large subbasins indicated with coloured areas in Figure 1. Each of these subbasins is hydrologically independent and corresponds to either the most upstream part of the main streams (Mississippi and Ohio) or a major tributary flowing into them. Each parameterized sub-project was manipulated by the SWAT-CUP interface for auto-calibration and uncertainty analysis with SUFI-2. At this stage we included only flow parameters in the auto-calibration in an effort to match observed hydrographs. Therefore, this study used 9 parameters (Neitsch et al., 2009): six related to groundwater (ALPHA_BF, GW_DELAY, GWQMN, RCHRG_DP, GW_REVAP, and REVAPMN), the curve number (CN2), the soil evaporation compensation coefficient (ESCO) and the available soil water capacity of the first soil layer (SOL_AWC(1)), in order to calibrate 13 individual SWAT projects with 900 iterations (runs) of each project. The CN was the only parameter altered by a percentage from the default value (±25%), while all other were modified with absolute values within sensible ranges. All projects were executed at once in a PC with 32 processors and 128 GB RAM, with a total runtime requirement of two days.

3. RESULTS AND DISCUSSION
The optimization of parameter values and uncertainty analysis indicated a p and r-factor for each data series indicating the percentage of observed data bracketed by the uncertainty bounds and the degree of uncertainty, respectively. Moreover, the $R^2$ of the comparison and the Nash-Sutcliffe Efficiency (NS) were estimated. The uncertainty measures and goodness of fit criteria are summarized in Table 1 for all 13 projects. All parameters were changed similarly within all 12-digit watersheds and HRUs of each subbasin considering the existing homogeneity in climate and ground characteristics (geology, land cover, topography). For most of the 13 calibrated subbasins, Table 1 indicates a high p factor and acceptable r factor followed by greater than 0.5 NS values, which are considered acceptable on a monthly basis (Moriasi et al., 2007). The results indicate that for the greatest part of the two basins SUFI-2 narrowed the uncertainties to acceptable levels. There are however two calibration points in the UMRB (Royalton and Muscoda) where the results are poor. This was likely due to the impact of lakes on hydrology, which attenuate peak flows and maintain significant baseflow in low-flow periods, a situation that could not be captured by the current wetlands parameterization.

From the best parameter values suggested by the algorithm (not presented here due to space limitations), it was concluded that SWAT tends to consistently over-predict flows in both UMRB and OTRB. The largest modifications occurred on the CN default values, with decreases up to 25%. However, one should consider the fact that conservation tillage types along with other existing in-field practices such as contour and strip-cropping systems and terraces have not been totally considered yet in this work. Their effect on
surface runoff is considerable and their simulation would require the reduction of the default CN values. Another interesting result is the modification of soil water capacity by up to ± 20%, which may indicate that the default values of this parameter have been over- or under-estimated in the soil database (see Part 1 for source of soil data).

Table 1. Uncertainty measures and goodness of fit criteria from the monthly SUFI-2 auto-calibration of flows within the UMRB and OTRB.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Subbasin (river)</th>
<th>Calibration point</th>
<th>p</th>
<th>r</th>
<th>R²</th>
<th>NS</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMRB</td>
<td>Upper Mississippi</td>
<td>Royalton</td>
<td>0.13</td>
<td>0.62</td>
<td>0.33</td>
<td>-5.81</td>
</tr>
<tr>
<td>UMRB</td>
<td>Minnesota</td>
<td>Jordan</td>
<td>0.80</td>
<td>1.20</td>
<td>0.68</td>
<td>0.63</td>
</tr>
<tr>
<td>UMRB</td>
<td>St.Croix</td>
<td>St.Croix Falls</td>
<td>0.93</td>
<td>1.74</td>
<td>0.75</td>
<td>0.65</td>
</tr>
<tr>
<td>UMRB</td>
<td>Chippewa</td>
<td>Durand</td>
<td>0.93</td>
<td>1.90</td>
<td>0.74</td>
<td>0.73</td>
</tr>
<tr>
<td>UMRB</td>
<td>Wisconsin</td>
<td>Muscoda</td>
<td>0.17</td>
<td>0.86</td>
<td>0.53</td>
<td>-3.82</td>
</tr>
<tr>
<td>UMRB</td>
<td>Iowa</td>
<td>Wappelo</td>
<td>0.65</td>
<td>0.98</td>
<td>0.79</td>
<td>0.71</td>
</tr>
<tr>
<td>UMRB</td>
<td>Skunk</td>
<td>Augusta</td>
<td>0.46</td>
<td>0.72</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>UMRB</td>
<td>Des Moines</td>
<td>Keosaua</td>
<td>0.83</td>
<td>1.09</td>
<td>0.78</td>
<td>0.75</td>
</tr>
<tr>
<td>UMRB</td>
<td>Rock</td>
<td>Joslin</td>
<td>0.49</td>
<td>1.21</td>
<td>0.56</td>
<td>0.08</td>
</tr>
<tr>
<td>UMRB</td>
<td>Illinois</td>
<td>Valley City</td>
<td>0.77</td>
<td>1.17</td>
<td>0.69</td>
<td>0.61</td>
</tr>
<tr>
<td>OTRB</td>
<td>Upper Ohio</td>
<td>Greenup</td>
<td>0.73</td>
<td>1.19</td>
<td>0.83</td>
<td>0.83</td>
</tr>
<tr>
<td>OTRB</td>
<td>Tennessee</td>
<td>Paducah</td>
<td>0.68</td>
<td>1.63</td>
<td>0.70</td>
<td>0.69</td>
</tr>
<tr>
<td>OTRB</td>
<td>Wabash</td>
<td>Mt.Carmel</td>
<td>0.81</td>
<td>1.18</td>
<td>0.85</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Note: Each calibration point was selected as the outlet of the 12-digit subwatershed located closer to the existing USGS flow observation station and its exact location is shown in Figure 1. The name of each large upstream subbasin is defined from the homonymous river. In the last columns, p and r are the percentage of observed data bracketed by the 95% ppu and the degree of uncertainty respectively, R² is the coefficient of determination and NS the Nash-Sutcliffe efficiency.

The next step in this calibration work was to consecutively execute SUFI-2 auto-calibration and uncertainty analyses for the intermediate or downstream areas to those already calibrated, which are indicated by the ‘white areas’ in Figure 1. Therefore, 5 new sub-projects were created and the best simulated flows from the upstream areas were inserted as point sources to the main streams. Flows were calibrated at St.Paul, Clinton and Grafton for the UMRB and Cannelton Dam and Metropolis for the OTRB (see Fig.1). Both predictions and uncertainty measures at these points were fully acceptable. The UMRB and OTRB models were finally validated by executing SWAT with the optimum sets of parameters across the landscape for a 20-year period in the past (1974-1994). Validation criteria (R² and NS) were acceptable for both river basins with an impressively good match between observed and calibrated flows and NO₃-N yields. Figure 2 depicts the comparison of predicted and observed monthly data at these locations for both the calibration and validation periods.

From the graphs and our experience with SWAT, we maintain that when total flow and its separate components (surface, baseflow) are well predicted and the models are appropriately parameterized (nutrient inputs), all kinds of pollutants (e.g. sediments, nutrients) should be within acceptable range with observed data. Especially NO₃-N, which is primarily transported by subsurface flow, have been very successfully predicted for such large scale applications, both within parts of the basins and at the total outlets, as shown on the graphs. These estimates strengthen the existing consideration of SWAT as a powerful tool for identifying critical pollutant source areas across complex landscapes when appropriately parameterized (Niraula et al., 2012; Panagopoulos et al., 2011).
4. CONCLUSIONS AND FUTURE RESEARCH
This paper presented a preliminary SWAT modeling of two large U.S. Corn Belt hydrologic systems based on a 12-digit watershed delineation, which can improve the representation of spatial input data, climate and management simulation. A key point of the present research is that the calibration and validation of such large hydrologic systems seems an endless task, which can always be updated with more accurate data and more robust assumptions of the reality. The Sequential Uncertainty Fitting algorithm embedded in the auto-calibration and uncertainty analysis SWAT-CUP program can facilitate the calibration of large SWAT models in reasonable time and at multiple times, something that seems unfeasible by following a manual approach. As proved from the results of this study, SWAT-CUP is an indispensable tool for identifying the magnitude of hydrologic processes across different parts of large river basins by narrowing the uncertainty of predictions. In the UMRB and OTRB, both flow and NO₃-N predictions were impressively good given the size and the complexity of the landscape simulated. On the other hand, sediment, P and organic N SWAT estimations, although already promising, have not yet achieved satisfactory levels of testing for alternative agricultural management scenarios designed to reduce nutrient loadings to the river system. The exact definition of the existing conservation practices (conservation tillage and other crop and soil management methods), along with improvements in simulating the existing wetlands and reservoirs will definitely improve the models' performance.

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Figure 2. Simulated versus observed time-series at the most downstream flow station points of UMRB (Grafton-left) and OTRB (Metropolis-right) for both the calibration and validation periods.
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