The Soil and Water Assessment Tool (SWAT) model has emerged as one of the most widely used water quality watershed- and river basin–scale models worldwide, applied extensively for a broad range of hydrologic and/or environmental problems. The international use of SWAT can be attributed to its flexibility in addressing water resource problems, extensive networking via dozens of training workshops and the several international conferences that have been held during the past decade, comprehensive online documentation and supporting software, and an open source code that can be adapted by model users for specific application needs. The catalyst for this special collection of papers was the 2011 International SWAT Conference & Workshops held in Toledo, Spain, which featured over 160 scientific presentations representing SWAT applications in 37 countries. This special collection presents 22 specific SWAT-related studies, most of which were presented at the 2011 SWAT Conference; it represents SWAT applications on five different continents, with the majority of studies being conducted in Europe and North America. The papers cover a variety of topics, including hydrologic testing at a wide range of watershed scales, transport of pollutants in northern European lowland watersheds, data input and routing method effects on sediment transport, and development and testing of potential new model algorithms, and description and testing of supporting software. In this introduction to the special section, we provide a synthesis of these studies within four main categories: (i) hydrologic foundations, (ii) sediment transport and routing analyses, (iii) nutrient and pesticide transport, and (iv) scenario analyses. We conclude with a brief summary of key SWAT research and development needs.

HYDROLOGICAL and water quality simulation models are being used increasingly to address an extensive array of water resource problems across the globe, including the effects of alternative best management practices (BMPs) and future climate change on streamflow and water quality. A plethora of such simulation models have been developed in recent decades to address various water quantity and water quality problems. These models are designed to operate across a range of scales (e.g., field versus watershed) and environmental conditions, and with varying levels of input data and model structure complexity. Dozens of review studies have been compiled that provide comparisons of either specific components or complete modeling packages for various subsets of existing water quality models (e.g., Borah et al., 2006; Breuer et al., 2008; Refsgaard et al., 2010; Daniel et al., 2011).

The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Williams et al., 2008) has emerged as one of the most widely used water quality watershed- and river basin–scale models worldwide, representing multiple decades of model development (Gassman et al., 2007; Williams et al., 2008; Arnold et al., 2012b). The model is supported by online documentation (Neitsch et al., 2011; Arnold et al., 2012a), multiple geographic information system (GIS) interface tools (e.g., Di Luzio et al., 2004; Olivera et al., 2006), other supporting software (e.g., White et al., 2014a, 2014c), and online resources (SWAT, 2013). SWAT has also proved to be highly flexible in addressing a wide range of water resource problems, as a result of the comprehensive nature of the model, strong model support, and open access status of the source code. The publication, citation, and search engine analysis reported by Refsgaard et al. (2010) confirm the widespread use of SWAT relative to several other leading hydrologic and water quality models.

The primary goal for this special collection of papers is to highlight important trends, successes, and problems related to...
the growing adoption of SWAT across a wide range of watershed scales and environmental conditions. The specific catalyst for this effort was the 2011 International SWAT Conference held in Toledo, Spain, which included over 160 presentations representing a wide variety of innovative investigations with SWAT in 37 countries. Most of the 22 papers included in this special section were originally presented at the 2011 conference and feature many of the key global application trends occurring with the model (Table 1) via studies performed on five different continents. Virtually all of the studies contained herein report some level of hydrologic testing. The majority also describe testing of SWAT output for one or more environmental indicators. Several additional themes are woven across these SWAT applications, as described in Table 1.

The purpose of this introductory paper is to present a concise overview of the studies included in the special collection, including innovative applications and adaptations of the SWAT code, as well as strengths and weaknesses of the simulation

<table>
<thead>
<tr>
<th>Study</th>
<th>Study region</th>
<th>Watershed(s)</th>
<th>SWAT version</th>
<th>Description of SWAT application†</th>
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</thead>
<tbody>
<tr>
<td>Almendinger et al. (2014)</td>
<td>Western Minnesota and eastern Wisconsin</td>
<td>717-km² Willow (MN) and 991-km² Sunrise (WI)</td>
<td>SWAT2000</td>
<td>Use of pond, wetland, and USLE P functions to depict sediment trapping in landscape depressions</td>
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<tr>
<td>Aouissi et al. (2014)</td>
<td>Northern Tunisia</td>
<td>418-km² Joumine</td>
<td>SWAT2009</td>
<td>Autocalibration of daily flow and nitrate output; evaluation of alternative nitrogen-related BMPs</td>
</tr>
<tr>
<td>Beeson et al. (2014)</td>
<td>North-central Iowa</td>
<td>788-km² S. Fork Iowa River</td>
<td>SWAT2009 (revision 510)</td>
<td>Effects of DEM resolution on slope estimation and resulting streamflow and pollutant estimates</td>
</tr>
<tr>
<td>Bieger et al. (2014)</td>
<td>Central China</td>
<td>3200-km² Xiangi</td>
<td>SWAT2009 (revision 477)</td>
<td>Streamflow and sediment testing as function of limited input and monitoring data constraints</td>
</tr>
<tr>
<td>Bothias et al. (2014)</td>
<td>Southwestern France</td>
<td>1110-km² Save ArcSWAT version 2009.93.7a</td>
<td>Estimation of daily exceedance of EU nitrate standard at watershed outlet</td>
<td></td>
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<tr>
<td>Bonumá et al. (2014)</td>
<td>Southern Brazil</td>
<td>4.8-km² Arroio Lino</td>
<td>SWAT2009</td>
<td>Impacts on sediment transport due to introduction of landscape units in SWAT</td>
</tr>
<tr>
<td>Cerro et al. (2014)</td>
<td>Northern Spain</td>
<td>53-km² Alegra subwatershed</td>
<td>ArcSWAT version 2009.93.5†</td>
<td>Evaluation of alternative nitrogen-related BMPs and likely exceedance of EU nitrate standards</td>
</tr>
<tr>
<td>Fohrer et al. (2014)</td>
<td>Northern Germany</td>
<td>50-km² Kielslau</td>
<td>ArcSWAT version 93.6</td>
<td>Evaluation and sensitivity of herbicide fate and transport for lowland region watershed</td>
</tr>
<tr>
<td>Hoang et al. (2014)</td>
<td>Funen Island in Denmark</td>
<td>622-km² Odense</td>
<td>SWAT2005</td>
<td>Streamflow and nitrate transport in tile-drained watershed; comparisons with DMS model output</td>
</tr>
<tr>
<td>Jeong et al. (2014)</td>
<td>North-central Texas</td>
<td>369-km² Upper White Rock</td>
<td>SWAT2009†</td>
<td>Effects of extreme urbanization and climate change on streamflow and associated stream health</td>
</tr>
<tr>
<td>Lu et al. (2014)</td>
<td>Funen Island in Denmark</td>
<td>4.28-km² Lillebaek</td>
<td>SWAT2009</td>
<td>Autocalibration of daily flow and sediment output; comparison of two sediment routing methods</td>
</tr>
<tr>
<td>Molina-Navarro et al. (2014)</td>
<td>Central Spain</td>
<td>87.8-km² Ompolíveda</td>
<td>SWAT2005</td>
<td>Evaluation of the utility of the model for assessing effectiveness of limno-reservoir</td>
</tr>
<tr>
<td>Ostojić et al. (2014)</td>
<td>Northwest Poland</td>
<td>593.7-km² Gąsawka, 2766.8-km² Warta</td>
<td>Not reported</td>
<td>Comparison of simulated vs. measured nutrient concentrations for three different sized watersheds</td>
</tr>
<tr>
<td>Paglieri et al. (2014)</td>
<td>Eastern Europe</td>
<td>803,000-km² Danube</td>
<td>SWAT2009</td>
<td>Autocalibration/validation approach for flow using nested watersheds for the Danube River basin</td>
</tr>
<tr>
<td>Piniewski et al. (2014)</td>
<td>Northeast Poland</td>
<td>28,000-km² Narew</td>
<td>SWAT2005</td>
<td>Climate change impacts on stream health; includes comparisons with WaterGAP model</td>
</tr>
<tr>
<td>Roebling et al. (2014)</td>
<td>Central Portugal</td>
<td>3685.5-km² Vouga</td>
<td>ArcSWAT version 2009.93.7†</td>
<td>Evaluation of nitrogen application rate BMP scenarios; economic impacts also reported</td>
</tr>
<tr>
<td>Santhi et al. (2014)</td>
<td>East-central U.S.</td>
<td>525,770-km² Ohio</td>
<td>SWAT2005†</td>
<td>BMP impact evaluation using a combined APEX-SWAT modeling system for the Ohio River basin</td>
</tr>
<tr>
<td>Watson and Putz (2014)</td>
<td>West-central Alberta</td>
<td>3.0-km² Mosquito subwatershed, 5.2-km² 1A, 9.5-km² Thistle, 15.0-km² Willow, and 13.3-km² Great Creek</td>
<td>SWAT Boreal Forest (SWATboreal)</td>
<td>Evaluation of different snowmelt algorithms in SWAT, a modified SWAT model applied to Boreal Forest conditions</td>
</tr>
<tr>
<td>White et al. (2014a)</td>
<td>Three example watersheds</td>
<td>Not applicable§</td>
<td>Description of SWAT Check screening tool software, including three example applications</td>
<td></td>
</tr>
<tr>
<td>White et al. (2014b)</td>
<td>Northeast Oklahoma and northwest Arkansas</td>
<td>4600-km² Illinois</td>
<td>SWAT2005†</td>
<td>Description, testing, and application of proposed modified in-stream P cycling submodel</td>
</tr>
<tr>
<td>White et al. (2014c)</td>
<td>Four southern U.S. states</td>
<td>Field sites ranging from 0.4 to 17.9 ha</td>
<td>SWAT2005†</td>
<td>Description of PPM Plus interface tool (based on SWAT); validation with field data presented</td>
</tr>
<tr>
<td>Zabaleta et al. (2014)</td>
<td>Northern Spain</td>
<td>4.8-km² Aixola</td>
<td>ArcSWAT version 2009.93.6</td>
<td>Impacts of climate change on flow and sediment loss, including sediment transport to reservoir</td>
</tr>
</tbody>
</table>

† BMP, best management practice; DEM, Digital Elevation Model; DMS, DAISY-MIKE SHE; USLE P, Universal Soil Loss Equation practice.
‡ Based on personal communication with authors (not reported in respective papers).
§ The SWAT Check software is compatible with SWAT versions 2005, 2009, and 2012 (2012 supersedes version 2011 stated in White et al. [2014a]).
results. The specific objectives are to provide (i) a synthesis of the key results of this set of studies categorized by foundational hydrologic results, pollutant transport and routing, and scenario applications and (ii) a summary of future SWAT research and development needs.

**Synthesis of Studies in the Special Collection**

The synthesis of the 22 papers that form this special collection (Table 1) is organized per the following four main categories: hydrological foundations, sediment transport and routing analyses, nutrient and pesticide transport, and scenario analyses. The specific watersheds simulated and SWAT versions used in each study are listed in Table 1.

**Hydrological Foundations**

Some level of hydrologic testing was performed in the majority of the studies presented here, including one or more of the phases described by Arnold et al. (2012b): sensitivity and/or uncertainty analyses, manual and/or automatic calibration, subsequent validation, and the use of graphical and/or statistical measures to judge model results. Three of the studies (Cerro et al., 2014; Santhi et al., 2014; Zabaleta et al., 2014) also report using the SWAT Check software described by White et al. (2014a) within their respective calibration analyses to confirm the appropriateness of water balance and other results.

**Statistical Testing Results**

The most commonly reported statistics are the coefficient of determination ($R^2$) and Nash-Sutcliffe modeling efficiency (NSE), described in detail by Krause et al. (2005). Many of the studies also report the percent bias (PBIAS), which measures the average tendency of modeled output to be larger or smaller than corresponding measured data (Moriasi et al., 2007). The majority of the studies also cite Moriasi et al. (2007) in regards to judging the success of SWAT testing results, especially their suggested criteria that NSE statistics computed for hydrologic and water quality model output should be $\geq 0.5$ or $0.75$ for monthly time-step comparisons in order for the model results to be considered satisfactory or good, respectively. Moriasi et al. (2007) further suggested “appropriate adjustments” in their criteria for annual or daily time-step evaluations. Table 2 lists the annual, monthly, and daily hydrologic $R^2$ and NSE statistics by frequency range reported within the present collection of papers. Nearly all of these statistics exceed Moriasi et al.’s (2007) criteria of 0.5 or greater for evaluation of monthly NSE comparisons, assuming an extension of the criteria to the $R^2$ statistics and other time steps. The strongest results are reported for the aggregated annual and monthly time steps, which is consistent with previous statistical compilations reported by Gassman et al. (2007), Douglas-Mankin et al. (2010), and Tuppad et al. (2011). However, over half of the studies report relatively strong daily $R^2$ and NSE hydrologic statistics, which mirrors trends of increasing numbers of SWAT studies reporting successful testing at a daily time step (e.g., Douglas-Mankin et al., 2010; Tuppad et al., 2011).

**Hydrograph and Flow Path Representation**

Graphical comparisons of simulated versus measured streamflows presented in several of the studies reveal that SWAT accurately or satisfactorily replicate observed total streamflow hydrographs. However, several studies explicitly state, or show via hydrograph comparisons, that daily and/or monthly peak flows were typically underestimated (Bieger et al., 2014; Boithias et al., 2014; Cerro et al., 2014; Fohrer et al., 2014; Hoang et al., 2014; Molina-Navarro et al., 2014; Pagliero et al., 2014; Santhi et al., 2014; Watson and Putz, 2014; Zabaleta et al., 2014). In contrast, some studies report overprediction of peak flows (Bieger et al., 2014; Hoang et al., 2014; Piniewski et al., 2014), weaknesses in seasonal representation of streamflows (Piniewski et al., 2014), or underprediction of low flow periods (Hoang et al., 2014). Hoang et al. (2014) also note that SWAT accurately replicated measured daily hydrographs but overpredicted surface runoff and conversely underpredicted subsurface drainage flow.

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**Table 2. Summary of Soil and Water Assessment Tool (SWAT) hydrologic calibration and validation statistic frequency analyses for the present studies.†‡**

<table>
<thead>
<tr>
<th>Frequency ranges</th>
<th>Annual</th>
<th>Monthly</th>
<th>Daily</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calibration</td>
<td>Validation</td>
<td>Calibration</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>NSE</td>
<td>$R^2$</td>
</tr>
<tr>
<td>0.90–1.00</td>
<td>3 1 2</td>
<td>6 12 5</td>
<td>6 12 4</td>
</tr>
<tr>
<td>0.80–0.89</td>
<td>3 2</td>
<td>5 12 6 7</td>
<td>2 3 1</td>
</tr>
<tr>
<td>0.70–0.79</td>
<td>1 2</td>
<td>4 8 2 7</td>
<td>3 6 3 5</td>
</tr>
<tr>
<td>0.60–0.69</td>
<td>1 3</td>
<td>1 3 1 3</td>
<td>2 9 8</td>
</tr>
<tr>
<td>0.50–0.59</td>
<td>1</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>0.40–0.49</td>
<td>1 1</td>
<td>1 1</td>
<td>1</td>
</tr>
<tr>
<td>0.30–0.39</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>0.20–0.29</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.10–0.19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00–0.09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Almendinger et al. (2014) report daily Nash-Sutcliffe modeling efficiency (NSE) validation statistics of 0.51 or 0.63 for the Willow River watershed in northwest Wisconsin, depending on whether a large precipitation event in October 2005 was included in the validation (i.e., the daily NSE improved to 0.63 when the event was excluded).

‡ Watson and Putz (2014) report six different sets of monthly and daily NSE calibration and validation statistics, corresponding to the six different snowmelt algorithms they investigated, for the five watersheds they simulated with SWAT. Only the standard SWAT snowmelt algorithm results are reported here (the results of the six snowmelt submodels were very similar).
Likewise, Fohrer et al. (2014) report good or very good overall hydrograph results but weaknesses in SWAT’s replication of hydrograph falling limbs and representation of groundwater storage depletion.

Watson and Putz (2014) report that simulation of snowmelt runoff with SWAT during multiple snowmelt seasons ranged from good to very good across the six different snowmelt submodels they tested. However, years with lower snowfall amounts and thus lower snowmelt runoff were not as accurately predicted. They also state that the use of more detailed snowmelt algorithms did not provide improved accuracy in estimating snowmelt runoff.

Input Data and Model Structure Limitations

Some weaknesses in the studies’ reported results can be attributed to problems resulting from input data. Two extreme examples are seen in Bieger et al. (2014), who report that only three climate stations were available for their simulation of the 3200-km² Xiangi watershed in central China, and Lu et al. (2014), who used 10-km gridded precipitation data to simulate the 4.28-km² Lillebaek watershed on Funen Island in Denmark. It is virtually certain that these inaccurate spatial representations of precipitation data negatively affected their SWAT hydrologic simulations. Zabaleta et al. (2014) and Watson and Putz (2014) also discuss problems with precipitation data inaccuracies.

Almendinger et al. (2014) modified SWAT to allow seepage from ponds, wetlands, and reservoirs to be added to lateral and groundwater flow paths, rather than be lost from the system, for the watersheds they simulated in Minnesota and Wisconsin. Beeson et al. (2014) modified SWAT to better represent pothole systems (described further in Beeson et al., 2011). They also discuss making larger-than-typical reductions in the runoff curve number (RCN; Williams et al., 2012) in their calibration process. They also state that the use of more detailed snowmelt algorithms did not provide improved accuracy in estimating snowmelt runoff.

Input Data Effects and Issues

Problems with temporal and/or spatial precipitation data accuracy were a probable source of inaccuracies in sediment yield results for some studies (e.g., Zabaleta et al., 2014; Bieger et al., 2014; Lu et al., 2014). Bieger et al. (2014) also note that the coarse resolution of the Digital Elevation Model (DEM), soil, and land use data they used, as well as problems in the transferability of the Modified Universal Soil Loss Equation (MUSLE) approach (Williams and Berndt, 1977), may have introduced further error in their sediment yield results. In contrast, Zabaleta et al. (2014) demonstrate the need to capture sensitive combinations of extreme slopes and land use, underscoring the importance of detailed watershed delineation schemes for some SWAT applications.

Beeson et al. (2014) evaluated the impact of slope values calculated from DEMs with different resolutions (90, 30, 10, and 3 m) on sediment load. Their assessment reveals that a 2.5-fold increase in slope occurred when using a high-resolution 3-m DEM instead of a low-resolution 90-m DEM, resulting in a predicted sediment loss increase of 130%. The authors suggest that care should be taken when using high-resolution DEMs to parameterize SWAT because this could result in significantly higher slopes, which can considerably alter modeled sediment loss. They also argue that the low-resolution DEMs are not consistent with older MUSLE technology.

Several of the studies (Almendinger et al., 2014; Bieger et al., 2014; Lu et al., 2014; Bonumá et al., 2014) report reducing the USLE Practice (P) factor (Wischmeier and Smith, 1978), which is normally set to 1.0 when no conservation practices are present in a field or watershed, to more accurately simulate soil erosion with the MUSLE equation in SWAT. These P factor adjustments reveal simplistic depictions of surface feature effects in the respective watersheds and show the need for more mechanistic methods to capture these processes.

Sediment Transport and Routing Analyses

Eight of the special collection papers report sediment yield and/or transport results (Almendinger et al., 2014; Beeson et al., 2014; Bieger et al., 2014; Bonumá et al., 2014; Lu et al., 2014; Santhi et al., 2014; White et al., 2014; Zabaleta et al., 2014). These studies describe a wide range of factors that impacted sediment yield and transport results, including watershed delineation and input data resolution, variations in landscape features, and sediment routing methods.

Baseline Sediment Yield Testing Results

Zabaleta et al. (2014), Almendinger et al. (2014), and Beeson et al. (2014) report mostly successful calibration and validation of sediment yield results, with $R^2$ and NSE values ranging from 0.47 to 0.94 for daily and/or monthly time-step comparisons. Bonumá et al. (2014), Bieger et al. (2014), and Lu et al. (2014), on the other hand, report weaker statistical results, especially NSE values, in their respective validation periods, which ranged between ~12.1 and 0.38. However, all three of these studies note important problems related to available measured sediment yield data. These include the need for more extensive datasets to perform in-depth model testing (Bonumá et al., 2014), lack of data reliability (Bieger et al., 2014), and difficulty in obtaining high statistical simulation accuracy due to the small magnitude of measured sediment yields (Lu et al., 2014).

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Sediment Routing Approaches and Issues

Lu et al.'s (2014) study demonstrates improvement in channel erosion estimates by calculating the erosion on the basis of excess shear stress compared with the existing channel sediment routing method used in SWAT (Neitsch et al., 2011) for lowland watershed conditions. Specifically, the proposed methods divide channel erosion into river bank erosion and river bed erosion, which is a more appropriate approach for modeling lowland areas, where bank erosion contributes more than surface erosion to sediment loads. The authors conclude that the modified approach more accurately simulated peak and low values of weekly flow-weighted suspended concentration and thus was more appropriate for the simulated lowland conditions.

Bonumá et al.'s (2014) work introduces a landscape sediment routing method into SWAT as follows: (i) determination of landscape units using a landscape delineation routine (Volk et al., 2007), (ii) computation of the landscape transport capacity (LTC) of sediment, and (iii) computation of sediment.
deposition by comparing the eroded sediment with the LTC to limit the sediment delivery from the hydrologic response units to the stream channels. The authors tested the new routing method versus the standard SWAT model for the Arroio Lino watershed in southern Brazil, concluding that the modified approach more accurately simulates sediment delivery for the steep and depositional topography that characterizes the study watershed, as evidenced by an improvement in the sediment yield PBIAS from −73 to −18%. The LTC method also indicated that 60% of the mobilized soil was deposited before it reached the stream channels, a phenomenon not captured by the standard SWAT model.

The study by Almendinger et al. (2014) demonstrates that SWAT was able to replicate the relatively low sediment yields measured at the watershed outlets the authors simulated in Minnesota and Wisconsin, primarily by accounting for the effects of depressional features. However, the authors note that “excessive parameterization” was required to perform the analysis. They further indicate the need to modify the SWAT code to better account for the surface water–groundwater interactions of depressional features in lowland landscapes as well as adopting the landscape position approach described by Volk et al. (2007) and Bonumá et al. (2014).

**Nutrient and Pesticide Transport**

Eight of the present studies report testing of nutrient transport simulations in SWAT (Aouissi et al., 2014; Boithias et al., 2014; Cerro et al., 2014; Hoang et al., 2014; Ostojski et al., 2014; Santhi et al., 2014; White et al., 2014b, 2014c), while Fohrer et al.’s (2014) study describes testing SWAT pesticide fate and transport. These authors provide further insights regarding input data uncertainty and/or structural limitations of SWAT for their respective analyses.

**Baseline Nutrient and Pesticide Transport Testing Results**

Cerro et al. (2014), Hoang et al. (2014), White et al. (2014b), and Fohrer et al. (2014) report mostly strong daily and monthly nutrient or pesticide baseline NSE statistics for their respective studies, the majority of which ranged from 0.37 to 0.88. Hoang et al. (2014) note a weaker daily nitrate NSE of 0.37 for reasons discussed below. Fohrer et al. (2014) report stronger daily statistics for the pesticide Metazachlor (NSE = 0.68; $R^2 = 0.62$) compared with the pesticide Flufenacet (NSE = 0.13; $R^2 = 0.51$), but graphical comparisons indicate that simulation of both pesticides replicated overall measured trends. Boithias et al. (2014) computed satisfactory PBIAS results of 10 to 27% for daily and annual nitrate loads for the Save River in France. Ostojski et al. (2014) also report satisfactory PBIAS results for their simulation of total nitrogen and total phosphorus for three different watersheds in Poland, although their overall results suggest considerable uncertainty in their simulated output. Aouissi et al. (2014) state that simulated nitrate concentrations varied in the same range as a limited set of corresponding measured concentrations for their SWAT analysis in Tunisia.

**Input Data and Modeling Structure Limitations**

Several studies in this special section describe uncertainty in determining accurate rates and timing of nutrient or pesticide applications due to several factors. These include having to base application assumptions on provincial-level data (Ostojski et al., 2014), deriving rate and timing from surveys of farmers in the study watersheds (Fohrer et al., 2014; Aouissi et al., 2014), or not taking into account permutations in crop rotations (Hoang et al., 2014). From a sensitivity analysis they performed, Fohrer et al. (2014) indicate that their SWAT watershed-scale pesticide transport results were highly sensitive to pesticide application rate and timing. Other input data issues include uncertainties related to assumed half-life and other key pesticide properties (Fohrer et al., 2014), as well as a lack of accounting for septic tank effects (Aouissi et al., 2014).

Hoang et al. (2014) note that SWAT simulated overall accurate nitrate loads but that the model simulated twice as much nitrate transport via groundwater flow compared with tile drain flow, which is inconsistent with other studies in the region. They also state that inaccurate partitioning among flow components likely contributed to the weaker replication of daily nitrate fluxes. Fohrer et al. (2014) also point to flow partitioning problems in their SWAT pesticide transport study and note that they were not able to directly simulate pesticide transport via tile drains or shallow aquifers due to structural weaknesses in the SWAT code. Boithias et al. (2014) report that 55% of the simulated nitrate transport in their study occurred in surface runoff, which is inconsistent with previous research showing lateral and groundwater as the main observed nitrate pathways.

White et al. (2014c) modified SWAT to more accurately simulate in-stream phosphorous (P) cycling for stream systems dominated by attached algae or strongly affected by point sources. The modified in-stream P cycling submodel features an equilibrium P concentration approach that is coupled to a particulate scour and deposition module. White et al. (2014c) applied the modified SWAT model to the Illinois River, which drains portions of Arkansas and Oklahoma, and which is greatly impacted by P discharge from point sources and widespread application of poultry manure to pasture areas. The modified approach captured the spatial and temporal trends of highly variable P concentrations and equilibrium P concentrations more accurately than did the approach used in existing SWAT codes.

**Scenario Analyses**

Several studies in this special section report scenario analyses results, including the evaluation of BMP impacts on water quality (Aouissi et al., 2014; Boithias et al., 2014; Cerro et al., 2014; Roebeling et al., 2014; Santhi et al., 2014) and climate change impacts on sediment yields or stream health (Jeong et al., 2014; Pinieński et al., 2014; Zabaleta et al., 2014). These analyses provide numerous useful insights, including effective approaches that can be used to meet European Water Framework Directive (EWFD) and other governmental agency water quality standard goals.

**Climate Change Impacts**

Zabaleta et al. (2014) present an analysis of climate change impacts on runoff and sediment yield for the Axiola watershed by inputting climate projections from four climate change projections, representing combinations of two general circulation models (GCMs) and two scenarios, for 2011 to 2100, in SWAT. Three of the GCM-scenario combinations suggested...
that runoff and sediments would decrease every year from 2011, but the other combination resulted in a predicted increase in runoff and sediments every year from 2011. These variations in annual sediment yield can be attributed to differences in the precipitation estimated between the GCMs.

Piniewski et al. (2014) and Jeong et al. (2014) used SWAT to study the impact of climate change on stream health for watersheds in northeastern Poland and north-central Texas, respectively. Piniewski et al. (2014) evaluated stream health on the basis of environmental flows (the quantity of water needed to maintain a healthy river ecosystem), while Jeong et al. (2014) used a set of 67 parameters developed for an EWF methodology to assess stream health. Piniewski et al. (2014) conclude that future climate change, based on two GCM projections for the period 2040 to 2069, will have a considerable impact on the majority of the Narew River aquatic ecosystems and that there is significant variability (both in terms of magnitude and spatial) in the projected impacts of climate change on the environmental flow indicators. In contrast, Jeong et al. (2014) split historical climate data into dry, wet, and average conditions, and historical flow data into pre-urbanized and post-urbanized periods, to evaluate alteration in stream health due to all three climate conditions. They also analyzed the effect of urbanization on stream health for a specific subwatershed where dramatic urbanization occurred during the 1980s and 1990s. Their results indicate that increasing urbanization had negative impacts on stream health and that dry weather had more impact on stream health than did wet weather.

**BMP Assessment Studies**

Bothias et al. (2014), Cerro et al. (2014), and Aouissi et al. (2014) each evaluated a 20% nitrogen application rate reduction scenario with SWAT for their respective study regions in France, Spain, and Tunisia. Relatively minor crop yield reductions were predicted: 5 to 9% (Bothias et al., 2014), 3% (Cerro et al., 2014), and 5% (Aouissi et al., 2014). Bothias et al. (2014) and Cerro et al. (2014) report that the number of predicted days exceeding the EWF nitrate concentration standard of 50 mg L⁻¹ declined by 62 and 50%, respectively, while Aouissi et al. (2014) indicate a 20% decline in average nitrate concentrations. Cerro et al. (2014) and Aouissi et al. (2014) also report nitrate reduction results for other application rate and/or filter strip scenarios. Roebling et al. (2014) assessed various N-fertilizer applications as best agricultural practice (BAP) scenarios, as a function of percent reductions of the baseline N application rates, for the Vouga watershed in central Portugal. They found no “win-win” results; i.e., reductions in N losses to the Vouga stream system were not beneficial enough to overcome agricultural production losses.

Santhi et al. (2014) interfaced SWAT with the farm-scale Agricultural Policy Environmental Extender (APEX) model (Williams et al., 2008), which they used to estimate cropland sediment and nutrient pollutant loads with more detailed representation of an extensive set of conservation practices. These practices include contouring, strip cropping, contour buffer strips, terraces, conservation tillage, filter strips, field borders, cover crops, and modifications in nutrient application rates and timing. Santhi et al. (2014) found that using conservation practices on cropland in the Ohio River basin reduced sediment, nitrogen, and phosphorus loads delivered to the Ohio River by 15, 16, and 23%, respectively.

**Conclusions and Future Research Needs**

In summary, the findings from the 22 studies reported in this special section provide solid evidence that SWAT is an effective tool for many different types of water resource and land management problems. The ongoing support of SWAT by government and private educational institutions together with its flexibility has resulted in increasing numbers of innovative applications and adaptations, helping to explain its growing adoption worldwide. But specific weaknesses encountered in some of the studies presented here clearly show that expanded testing and/or specific improvements are needed, as discussed below.

**Hydrologic Interface**

Several of the present studies report RCN-related calibrations (e.g., Aouissi et al., 2014; Beeson et al., 2014; Bothias et al., 2014; Cerro et al., 2014; Zabaleta et al., 2014), which is common in many SWAT studies due to the empirical nature of the method (Gassman et al., 2007; Arnold et al., 2012b). These results stress the need for further RCN-related research, as well as more investigation of the Green-Ampt method (Green and Ampt, 1911), which has been tested in very few SWAT studies (e.g., Ficklin and Zhang, 2013; King et al., 1999). Alternative RCN approaches have also been used in modified SWAT applications (e.g., Easton et al., 2008; Kim and Lee, 2008), which warrant further research and possible incorporation into standard versions of SWAT.

**Erosion Estimation and Sediment Routing**

The studies performed by Almendinger et al. (2014), Beeson et al. (2014), Bieger et al. (2014), Bonumá et al. (2014), and Lu et al. (2014) indicate that continued testing and development is required for the sediment delivery and sediment routing algorithms used in SWAT, including (i) expanded testing of sensitive inputs to the MUSLE sediment delivery routine, possible modifications to the MUSLE algorithms, and/or possible incorporation of alternative sediment delivery methods (e.g., Lenhart et al., 2005); and (ii) improved routing methods for different types of landscapes, which could also account for depressions, riparian areas, and other landscape-specific features. The LTC approach introduced by Bonumá et al. (2014) is particularly promising, building on the “landscape unit” approach described by Volk et al. (2007) and Arnold et al. (2010).

**Subsurface Tile Drainage**

SWAT has been used successfully in previous watershed applications that included subsurface tile drainage (e.g., Beeson et al., 2011). However, the results presented by Hoang et al. (2014) indicate that SWAT apparently underpredicted subsurface tile drainage flows. Fohrer et al. (2014) also comment on the need to decouple SWAT tile drainage pesticide transport from subsurface lateral transport. These findings reveal the need for further testing of both the original SWAT subsurface tile drainage algorithms and new tile drainage algorithms developed.
Nutrient Cycling and Transport

Modifications in nutrient routines reported by White et al. (2014b) reveal the need for improved in-stream P cycling algorithms in SWAT. These results confirm previous conclusions by Borah et al. (2006) and Breuer et al. (2008), who stated that extensive future research will be required to improve various SWAT soil, impoundment, and in-stream nutrient cycling components to better replicate actual physical nutrient cycling processes.

Uncertainty and Sensitivity Analyses

Several of the studies herein report performing sensitivity analyses (e.g., Aouissi et al., 2014; Fohrer et al., 2014; Hoang et al., 2014; Zabaleta et al., 2014) or autocalibration (e.g., Becson et al., 2014; Ostrojski et al., 2014; Piniewski et al., 2014; Watson and Putz, 2014) of selected subsets of SWAT inputs. However, these studies report no explicit uncertainty analysis results, despite extensive uncertainty evident in many of the studies (e.g., Bieger et al., 2014; Ostrojski et al., 2014). These results underscore the need for increased uncertainty analyses in future SWAT applications per the protocols outlined by Arnold et al. (2012b).

Model Validation

Hoang et al. (2014) note that users of SWAT need to bear in mind that the calibrated modeling results should reasonably reflect the actual hydrologic and pollutant transport processes, similar to some of the issues discussed by van Griensven et al. (2012). Refsgaard et al. (2010) also cited several other important calibration and validation issues relevant to SWAT applications, including unrealistic calibration efforts due to calibrating too many model parameters. In addition, further research is needed that builds on the influential statistical evaluation criteria suggested by Moriasi et al. (2007).

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