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Field to watershed-scale water quality adaptations to address a changing world

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Abstract Limited input data per desired simulation area challenges watershed models capabilities. Weather input is essential for accurate modelling of hydrological processes, yet many world regions do not have these data readily available. The Agricultural Policy eXtender Model (APEX) offers a spatial weather generator to assist these data scarce regions. APEX can also simulate small landscape to large scale watersheds with steep rainfall gradients. The APEX weather generator creates daily weather values that are correlated in time and space, based on monthly weather statistics using a probabilistic method, that are then linked to flow, water quality and soil properties. Recent developments in APEX on streamflow routing methods include the addition of two new routing methods: Storage with Variable Slope and Variable Storage Coefficient. These methods improve flow and in-stream water quality simulation results by incorporating the diffusive momentum in streamflows and channels that are mildly sloped or affected by flashy floods. The alterations in routing allow for proper accounting of the new algorithms in development for contaminants of emerging concern (CEC) including hormones, metals and insects/pests, in addition to improving wetland/riparian zone impacts on these constituents. The CECs are being linked to soil physical and chemical properties (i.e. metals linked to soil saturation and clay content). Carbon, nitrogen, and phosphorus pools have also been altered.

Key words water quality; water quantity; APEX; EPIC; SWAT; model; simulation

INTRODUCTION

The United States has made tremendous advances in the past 25 years to improve water quality conditions by controlling point source pollution from industries and sewage treatment plants. However, nonpoint source pollution (NPS) remains the nation's largest source of water quality impairment as evidenced by approximately 40% of the surveyed rivers, lakes and estuaries that are not meeting recreation standards (i.e. fishing or swimming). Agriculture is the leading contributor to water quality impairments, degrading 60% of the impaired river miles, and is responsible for half of the impaired lake acreage surveyed (USEPA, 1992). Surface runoff from urban areas is the largest source of water quality impairments to surveyed estuaries. The most common NPS pollutants are sediment and nutrients (USEPA, 1992). Increasingly common NPS pollutants include pesticides, pathogens, salts, oil, grease, toxic chemicals and heavy metals. Sources of these constituents can be agricultural land, small- and medium-sized animal feeding operations, and disturbed areas such as construction sites.

The USA has made significant headway in addressing NPS pollution. The US Environmental Protection Agency (EPA) implements several Clean Water Act Programs such as CWA 319 projects and Total Maximum Daily Load (TMDL) to control NPS pollution; the National Oceanic and Atmospheric Administration (NOAA) implements programs in coastal zones; the US Department of Transportation (USDOT) focuses on erosion control from roads, highways, and bridges; the US Department of the Interior (USDOI) administers programs to help states manage NPS pollution by providing technical assistance and financial support; and the US Department of Agriculture (USDA), along with Farm Services Agency (FSA) and US Forest Service (USFS), implements several incentive-based conservation programs to help control NPS pollution from agriculture, forestry and urban sources.

All government agencies have benefited from taking a geospatial approach to address NPS water quality pollution problems by analysing the upstream contributing area that drains into the receiving water body. A trio of models developed at the Blackland Research and Extension Center in Temple, Texas, are at the forefront of these efforts: EPIC (Environmental Policy Integrated

Climate) (Williams, 1990), APEX (Agricultural Policy/Environmental eXtender) (Williams & Izaurralde, 2006) and SWAT (Soil and Water Assessment Tool) (Arnold *et al*., 1998). These models represent different simulation capabilities based on how the model processes are summed per geospatial discretization (i.e. hydrologic response unit (HRU: combination of land use, slope, and soil type). EPIC is a non-spatial tool, intended for use at the field-to-farm scale (hectares to a few square kilometres), while APEX expands EPIC to cover small to large watersheds (10s to 1000s of km^2) that may include several farms and many fields with a high level of water quality and hydrological detail. APEX is explicitly spatial with routing for above and below groundwater flow through the landscape. SWAT (Soil and Water Assessment Tool) focuses on very large (>10 000s of km^2) by commonly utilizing the results of APEX outputs to capture the process details, and then utilizing the APEX outputs as inputs to simulate a large region resulting in a simplified process summary output for hydrology, sediment and nutrients. EPIC/APEX explicitly model plant growth and crop management as part of the simulations and can include economic estimates.

All of the models are used worldwide to examine the environmental consequences of agricultural practices to assist land managers and policy decision makers. We present five case studies highlighting some of these uses and their respective properties. Modelling tools have the capability to provide science-based results to evaluate existing conservation programs, develop new programs, and manage water quality issues.

Case Study 1: EPIC estimating agricultural pest management implications of climate change

A development to EPIC/APEX currently underway is the incorporation of a pest population model. Currently EPIC/APEX provide only economic and environmental cost estimates of pesticide application. The new pest population model will permit assessment of the benefits of pesticide applications. A recent study using EPIC investigated the likely changes in pest potential of a suite of insect pests of corn and soybeans in the American Midwest (Taylor *et al*., 2013). EPIC was linked to GILSYM (Generalized Insect Life System Model), a programmable model capable of simulating a wide range of insect life histories. GILSYM simulates daily cohorts through their life-cycle with eggs laid on a given day constituting a cohort that progress through their larval, pupal and adult stages. Using stage-specific developmental thresholds and temperature dependent growth rates, the model is driven by day-degrees. Food availability and mortality due to natural enemies and other hazards also modify the cohorts daily.

Most broad-acre field crops are annuals whose ranges can change rapidly under agricultural management; insects being mobile can also quickly change their distributions. Thus, one might expect these crops and their insect pests to migrate north together as the climate warms. However, as the rate of insect development and population growth is proportional to temperature above a threshold, and plant growth rate above a temperature threshold depends on the amount of sunlight and availability of moisture, climate change could lead to differential changes in the growth rates of crops and pest populations. Because the relative phenologies of crops and pests play an important role in pest management decision-making, any phenological changes could have profound effects on crop production if insect–plant interactions change. Climate warming could therefore alter pest status with environmental, economic and societal implications as farmers adjust their pest management practices to cope with changing pest pressures.

Simulations of the linked EPIC/GILSYM model were run at the resolution of the county for an eight state region (~560 000 km^2) of the Corn Belt: Illinois, Indiana, Iowa, Kansas, Kentucky, Missouri, Nebraska and Ohio (Taylor *et al*., 2013). More than 60% of USA corn and soybeans are produced in this region in which 60% is devoted to corn and soybeans agriculture. Plant–insect simulations were driven by temperature and precipitation output from the IPCC (2007) climate scenario SRES-B1 using the GFDL CM2.0 climate model. This represents the lower emissions path in which CO_2 is assumed to stabilize at about 550 ppm by the year 2100.

Nine insect pests of corn and/or soybeans representing a range of life history strategies were simulated. All are currently a sporadic and occasionally serious pest of one or other crop in all or part of the study area. Output from the simulations indicated the anticipated productivity gains from increased temperatures and CO_2 were offset by increased pest pressure on both crops. Insect abundance, overwinter survival of resident species, and number of generations per year all increased, while invasion by migrants occurred earlier. With the most dramatic changes occurring in the first half of the 21st century, in the coming century population growth will start earlier and peak later, exposing crops to more abundant pests for longer. The changes in life history parameters were all strongly correlated with the increase in annual day-degree accumulations from 1901 to 2100. Insects with the higher developmental thresholds presented a larger problem for pest managers as they gain the most benefit from elevated temperatures.

The current versions of EPIC and APEX have only weak linkage with GILSYM; the revisions underway will more closely integrate the insect model with the soil/water model to better represent the interaction between pest and crop. It seems unlikely that a closer integration will materially change the conclusions of this preliminary climate change study, but the initial results are sufficiently alarming to warrant closer study.

Case Study 2: APEX estimating environmental impact of transition from conventional to organic livestock management

In a study using APEX, Taylor and colleagues at The Ohio State University simulated conventional and organic pasture management, and pasturing and intensive rotation of beef cattle to assess their likely effects on several aspects of water quality and quantity (Taylor *et al.*, in prep/pers. comm.). These four management strategies were simulated in Little Mill Creek, Coshocton County, Ohio. Little Mill Creek is a 22 km^2 headwater basin flowing into the Ohio River via the Muskingum River (Fig. 1). Daily flow data were recorded at seven weirs from 1 January 1946 to 30 September 1971 (9404 days). The area of the watershed above the lowest weir (97) is 1850 ha. The watershed was divided into 53 sub-areas above Weir 97. Four 15-ha fields were defined in the pasture area in the headwaters of Little Mill Creek. The fields were defined so they could be divided into 15 1-ha paddocks to assess the impact of intensive rotational grazing on the downstream water quality.

The APEX model was calibrated for flow at each weir from 1946 to 1970 by tuning APEX parameters to maximize the correlation between observed and predicted weekly flow ($r^2 \sim 55\%$). The model was run from 1971 to 2010 driven by climate data from a nearby (~30 km) NOAA station to derive a relationship between stocking rate (16 to 34 animals per field) and phosphorus (P), nitrogen (N), and sediment runoff at the field edge and at the downstream weirs. Conventional pasture management was simulated using inorganic pasture fertilization and organic management was simulated using chicken manure; both methods are common in this part of Ohio. In addition to pasture fertilization practice, this study also investigated the impact of grazing practice on water quality. Four 15-ha fields were defined in the Little Mill Creek headwaters area. In one set of simulations, a herd (of 16–34 head) grazed a field for the entire season (a practice called pasturing). In the second set of simulations a practice called rotational intensive grazing was simulated. In these simulations, the fields were divided into 15 1-ha paddocks, and the herds grazed in a single paddock for only one day and moved to a new paddock each day. Thus, each paddock was grazed for one day in a 15-day rotation, permitting regrowth of fresh forage. The four fields provided replication.

As expected, field edge and downstream N, P and sediment increased with stocking rate, the effect declining with distance downstream. Nutrients and sediment runoff were not discernible at Weir 97 (Fig. 1), 7-km downstream, but at 2-km downstream the signal was still strong. Manipulation of the input parameters describing the fertilizers indicated that the elevated runoff with organic management was due almost entirely to the slow decomposition and penetration of chicken manure. Simulations indicated that nutrient and sediment runoff 2-km downstream were two to four times greater with organic management, and the relationship between runoff and stocking rate was steeper with rotational grazing than with pasturing. Other simulation experiments examined the effect of slope on manure erosion and downstream water quality. Interestingly, phosphorus, nitrogen, and sediment runoff were minimized at moderate field slopes. Perfectly flat, level fields

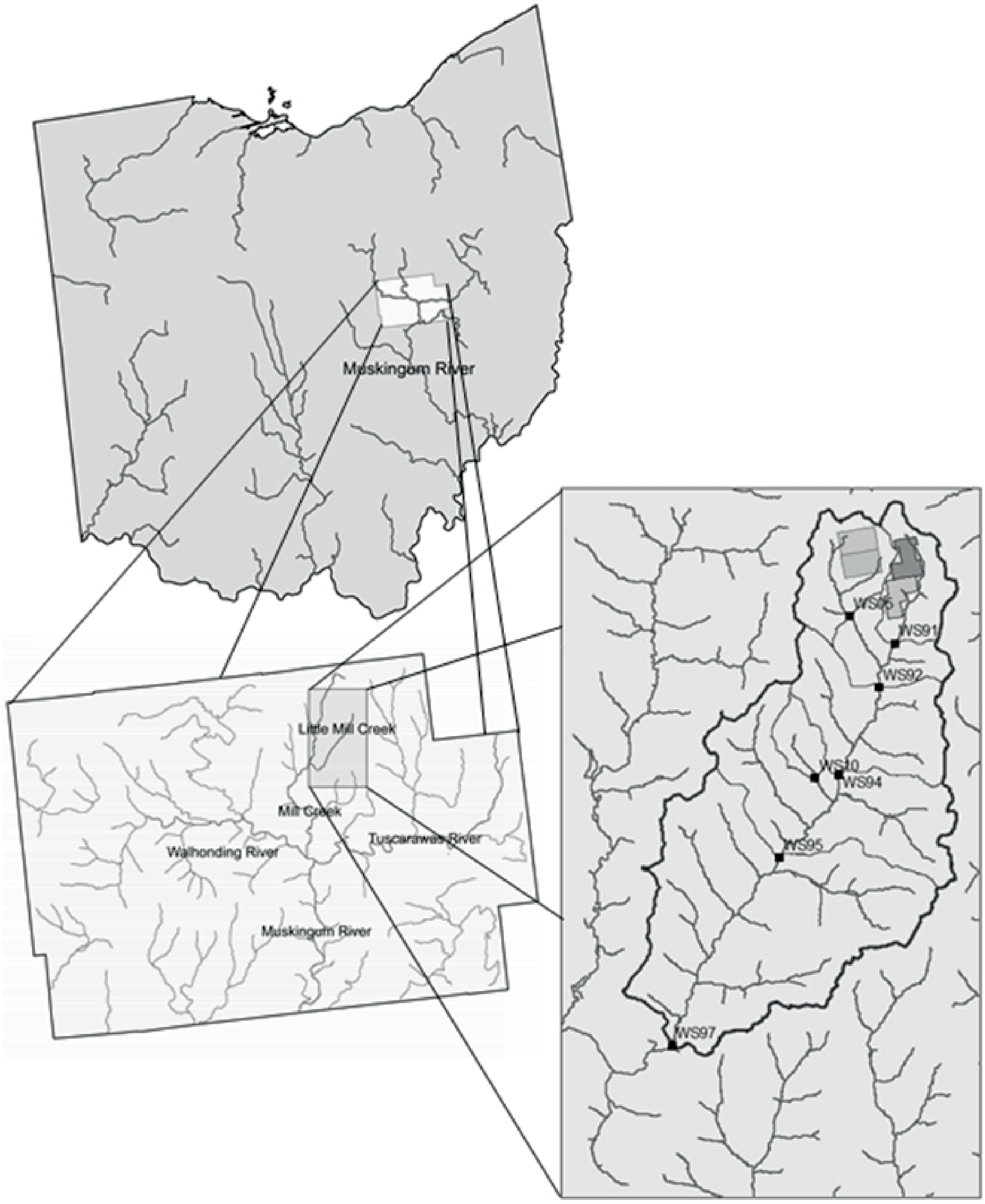

Fig. 1 Upper Mill Creek watershed in Coshocton County, Ohio showing the weirs and four headwater pastures used in the organic transition simulations.

contributed more runoff, possibly because the slower runoff was able to erode more manure, while runoff from extreme rainfall events eroded more manure on very steep slopes.

It is assumed that because neither pesticides nor inorganic fertilizers are used in organic agriculture, their environmental impact is less than conventional agriculture, if not actually beneficial to the environment. While this common belief is supported by scientific data on soil quality and biodiversity, the impact of organic farming on water quality and quantity is poorly understood and almost nothing is known about the impacts of organic animal production systems on water quality and quantity. Simulating organic farm management schemes with APEX has provided a powerful first step in understanding the liabilities as well as benefits of the transition to organic agriculture.

Case Study 3: APEX generating climate data in Cowhouse Creek

In regions with a scarcity of climatic data, application of watershed simulation tools is a challenging task because EPIC/APEX and SWAT require daily precipitation as the essential inputs; other weather variables are supplementary inputs for the geo-physical and cropping system submodels. EPIC and APEX can use monthly data to generate the daily data required using a program that is freely available. The APEX spatial rainfall generator (SRGEN) estimates daily precipitation for each sub-area based on a discrete-time random process with a conditional probability distribution using monthly statistics such as mean precipitation, standard deviation, skew coefficient and number of days of rain. The basic algorithm for generating daily precipitation is based on a first-order Markov Chain model (Nicks, 1974) and the WGEN model (Richardson & Wright, 1984). Each day, a random number is generated and compared with the wet–dry probability and a precipitation event occurs if the probability criterion is met for the day. To consider a generated precipitation that is spatially distributed, a rectangular domain is formed outside the watershed such that the spatial domain covers the whole watershed with lateral and longitudinal distances three times larger than the maximum lateral and longitudinal distances of the watershed. Monthly weather generator parameters for up to 10 stations may be input along with the fraction of the watershed they represent. The fractions are used to form a cumulative probability distribution. Storm events are generated from a set of 12 weather parameters chosen randomly from the cumulative distribution.

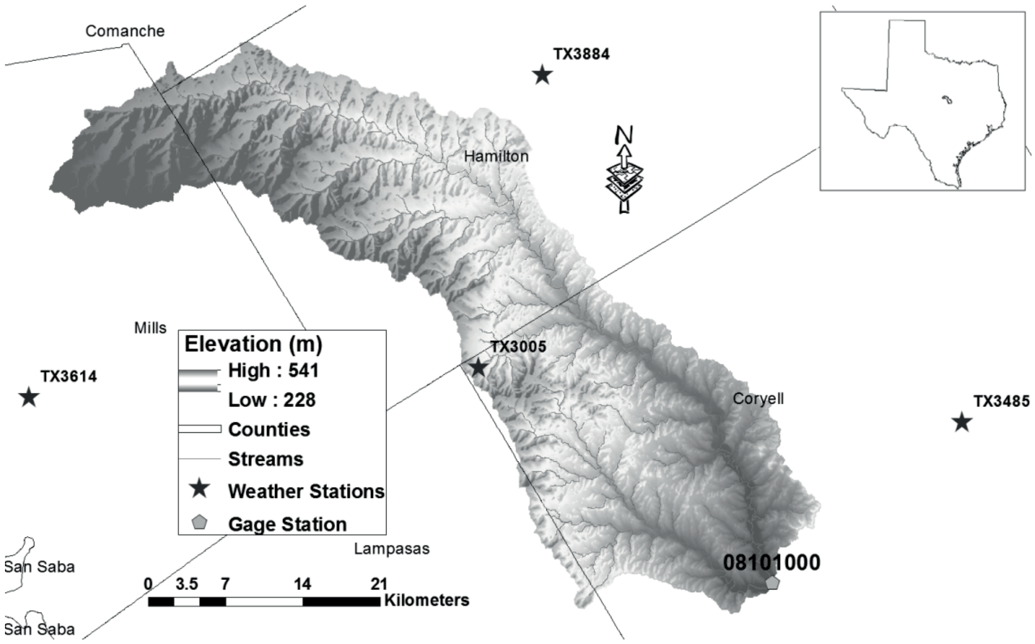

Fig. 2 Location of Cowhouse Creek in north central Texas.

Cowhouse Creek is located in north central Texas and runs southeast for 150 km through Hamilton and Coryell counties into Belton Lake in Bell County. It is a tributary of the Brazos River, most of which is rangeland within the Lampasas Cut Plain. The Cowhouse watershed (1178 km^2) is the drainage area of the USGS gauge site 08101000 (Fig. 2). The creek traverses variable terrain surfaced by stony clay loams and fine sandy loams featuring a variety of rangeland vegetation including juniper, oak, mesquite and brush. The 30-year average annual precipitation is 775 mm. The major soil series are silty-clays, clayey-loams, and clayey-skeletal, smectitic, thermic lithic Haplusols. Measured daily precipitation data are available at four raingauges from 1964 to 2009. Average annual precipitations at the four gauges present a spatial rainfall gradient of 1.2 mm km^{-1} longitudinally (positively increasing from east to west) and 2.9 mm km^{-1} latitudinally (positively increasing from south to north).

Because actual precipitation was measured at the four point locations in the watershed, the precipitation generated by SRGEN may not be directly compared with the measured historical precipitation at each sub-area for evaluation of the spatial distribution of rainfall. Average annual precipitation of individual sub-areas produced by: (1) measured gauge data, (2) SRGEN, and (3) WXGEN are shown in Fig. 3. When measured daily precipitation data are available, APEX uses the nearest raingauge from each sub-area. Thus, the resulting precipitation map shows five discrete divisions in the watershed, each with the same precipitation. As TX3005 is located within the watershed while other gauges are not, its contributing area is the largest followed by TX3884. The unnaturally abrupt changes in the precipitation between sub-areas near the border of each of the divisions are likely to increase uncertainties in the hydrological simulated output. When precipitation was generated by SRGEN, the precipitation was distributed, varying from 698 mm to 852 mm across the watershed. The annual precipitation values at the nearest sub-areas to the rain-gauges presented excellent results when compared to the average gauge values. Though SRGEN does not incorporate temporal correlation of meteorological characteristics, its spatial correlation to monthly statistics was excellent. The precipitation generated using SRGEN is clearly superior to the old point weather generator using monthly statistics at only one location extrapolated across the watershed. The maps also highlight the limitation of WXGEN, where TX3005 was used to generate precipitation with the resulting annual average precipitation being uniform throughout the entire watershed.

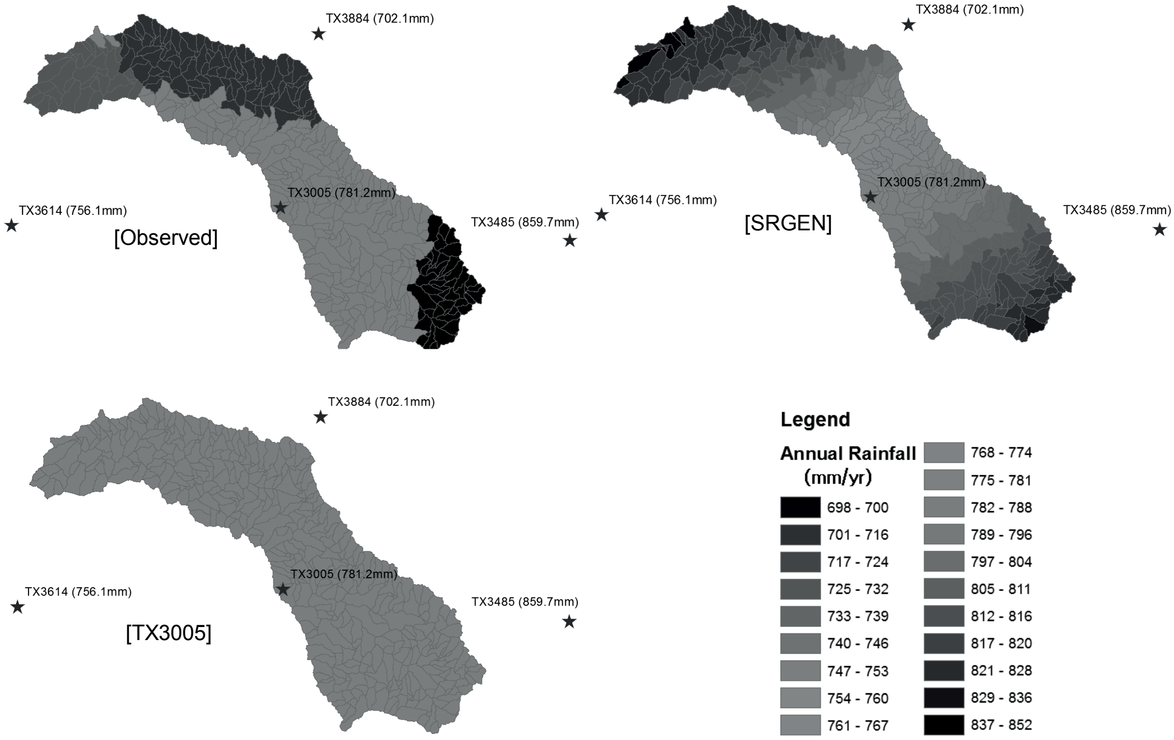

Fig. 3 Spatial distribution of annual rainfall showing: (1) measured raingauge values (top left), (2) rain generated using SRGEN (top right), and (3) generated using WXGEN with TX3005 (bottom).

The ability to reproduce the actual monthly trends is a crucial component for a plant simulation model like APEX because seasonal variation of climate dictates the plant growth mechanisms that in turn influence the overall hydrological response of the watershed. The SRGEN precipitation monthly statistics require monthly mean precipitation as the essential information. There are additional optional monthly values that help characterize the climate of the watershed, including monthly standard deviation of daily precipitation, monthly skew coefficient for daily precipitation, monthly probability of wet days after dry days, monthly probability of dry days after wet days, and monthly maximum half hour rainfall. Since historical daily precipitation data was available at all four gauges, the full monthly statistical data were estimated and entered for SRGEN in the Cowhouse watershed. As shown in Fig. 3, the monthly average precipitation generated by SRGEN compares very well to actual rainfall at the whole watershed scale. Little bias (<4%) was observed overall, but differences were observed in March (–22%), July (+24%), and August (+22%). Overall, the generated precipitation reproduced the actual pattern of wet months and dry months well. WXGEN tends to extrapolate the climatic characteristics of the location, forcing uniform tendency and variability of the referencing gauge into the entire watershed. Therefore, the seasonal variability of precipitation of the watershed tends to be skewed by the properties of the gauge, which imposes a significant uncertainty in the generated precipitation.

The appropriateness of the spatial weather generator may be demonstrated by presenting the daily runoff and water quality variables more closely reproduced using SRGEN compared with WXGEN, the original point weather generator. With generated daily precipitation by SRGEN, the predicted flow matched well to the calibrated flow though a slight underestimation was observed in the high flow regime. The result compared well with WXGEN on TX3485 and TX3884, each representing a wet location (annual PCP = 872.9 mm) and a dry location (annual PCP = 699.8 mm) in the Cowhouse watershed. With TX 3485, WXGEN-simulated flows are consistently higher than the calibrated flow and the difference increases up to 40% on high flows. As streamflow continues from an upstream sub-area to the downstream outlet, the error and uncertainty associated with individual sub-areas tend to accumulate, but SRGEN-simulated flows were extremely well aligned on the unit slope line. Comparative analyses on water quality variables including sediment yield, nitrate, soluble P, organic N and organic P presented improved results over WXGEN mainly due to the increased spatial accuracy in the generated precipitation.

The Cowhouse watershed case study demonstrated that the improved accuracy achieved in the precipitation generator transfers to the APEX hydrology and water quality resulting in an excellent performance of the model on simulated discharge, sediment and nutrient yield. Spatial interpolation of daily weather data is useful to refine the resolution of weather station data if multiple weather stations are available within the proximity of a study area. SRGEN can be useful for modelling watersheds that do not have weather stations nearby or if interpolated precipitation values do not represent the local weather properties. The encouraging results from the Cowhouse watershed case study demonstrate that APEX can be a useful tool for managing water resources and for prioritizing implementation of watershed conservation practices.

Case Study 4: SWAT estimating nonpoint source pollution in the Bosque River watershed

Nonpoint source pollution comes from many diffuse sources spread across the watershed and hence, they are complex to fully assess. Thus, water quality simulation models are useful to assess the nonpoint sources in large watershed with mixed land uses, soils, and multiple sources, where observed data are inadequate to give a complete assessment. An example of the SWAT model being used for a TMDL applications in the USA is Texas's Bosque River that drains into Lake Waco, a source of drinking water for Waco city. This watershed has nearly 100 dairy operations, with more than 40 000 milk cows. Manure produced from these animals is applied on 95 km^2 of fields. Fertilizers are applied on cropland, pasture and urban land. Effluents from municipal waste-water treatment plants discharge in the river system. Dairy manures and wastewater treatment plants are major sources of soluble phosphorus pollution to the Bosque River and Lake Waco. As a result, Lake Waco is experiencing eutrophication and algal growth. The SWAT model was calibrated for flow, sediment and nutrient transport and applied to quantify the effects of best management practices (BMPs) related to dairy manure management and municipal wastewater treatment plant (WWTP) effluent (Santhi *et al*., 2001).

While the existing scenario represents the current land management conditions, WWTPs, dairy cattle population and manure application area in the Bosque watershed (Fig. 4), the future scenario represents the projected conditions in terms of population growth, urbanization, WWTPs, dairy cattle population and manure application area in 2020. Scenario E represents modifications added with a suite of dairy and WWTP BMPs (management measures) to the existing conditions. Scenario F represents modifications added with a suite of dairy and WWTP BMPs to the future conditions. The probability exceedence plots (Fig. 4) developed for various dairy and point sources scenarios provide information on the probability of achieving a particular load of mineral phosphorus (min P) through a BMP. The min P loadings increased in the future condition scenario compared to the existing condition scenario by 29% at Valley Mills in the Bosque watershed (Fig. 4). Scenarios E and F showed reductions of 57% and 48%, respectively, at Valley Mills from the future scenario. Scenario E indicated that at existing conditions, implementation of the BMPs would come closer in achieving the desired water quality goals established for this watershed. However, with year 2020 future growth conditions, more stringent controls are required to meet the water quality goals.

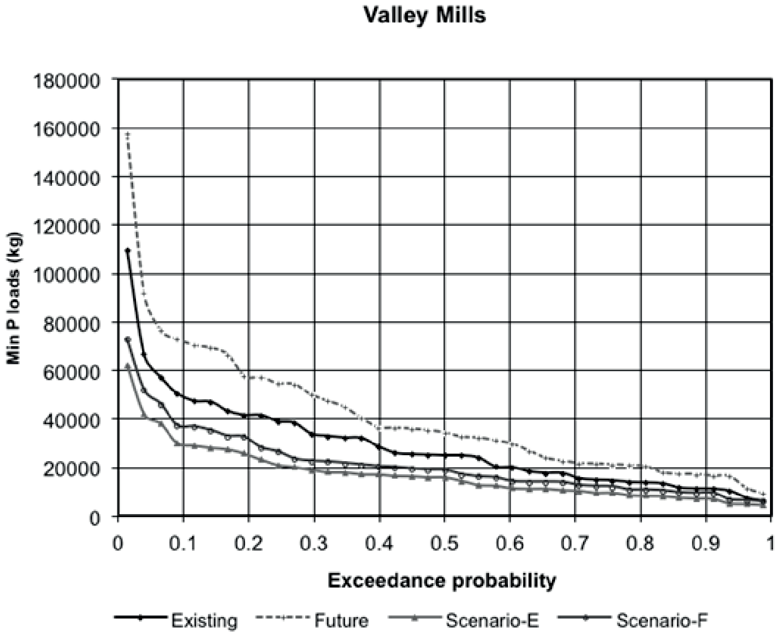

Fig. 4 Exceedence probability of mineral phosphorus (min P) loadings for different BMPs at Valley Mills in the Bosque River Watershed, Texas.

Case Study 5: APEX & SWAT estimating nitrogen flux in the Mississippi-Atchafalaya River basin

The Mississippi-Atchafalaya River basin (MARB) is a very productive agricultural region in the USA, exporting 60% of grain production in the country. Agriculture in this basin is reported as being a major contributor of nutrient and sediment loadings to the Mississippi River and Northern Gulf of Mexico (Scavia *et al*., 2003). Conservation practices continue to be implemented by the USDA and other agencies to reduce soil erosion, nutrients and pesticide losses from farm fields and preserve the MARB. Reduced pollutant losses from the field due to conservation, eventually result in improving the water quality of the rivers and streams in the basin (USDA-NRCS, 2012).

Potential water quality improvements expected in the MARB due to currently established conservation practices and additional conservation treatments are simulated using the APEX and SWAT models as part of the Conservation Effects Assessment Project (Mausbach & Dedrick, 2004). The “no practice scenario” represents the landscape conditions in the MARB without conservation practices. The current conservation practice scenario represents the landscape conditions with currently established conservation practices implemented on cultivated cropland and CRP land in the MARB. Current conservation practices simulated include: (1) Structural Practices such as contour farming, strip cropping, contour buffer strips, terraces, grass terraces and tile drain, grade stabilization structures, grassed waterways, filter strips and borders; and

(2) Cultural Management Practices such as nutrient management practices for N and P, residue and tillage management practices, conservation crop rotation and cover crops. The additional conservation treatment practice scenario represents treating all the under-treated cropland areas that generate a higher amount of field losses of nutrients, in addition to the commonly prescribed conservation practices (with any of the practices listed above) to generate field losses of nutrients within acceptable levels set by the NRCS. Water quality improvements in the MARB are indicated through comparisons of total nitrogen loads for three agricultural conservation scenarios at the outlets of various river basins in the MARB, and loads discharged to the Gulf of Mexico (Fig. 5).

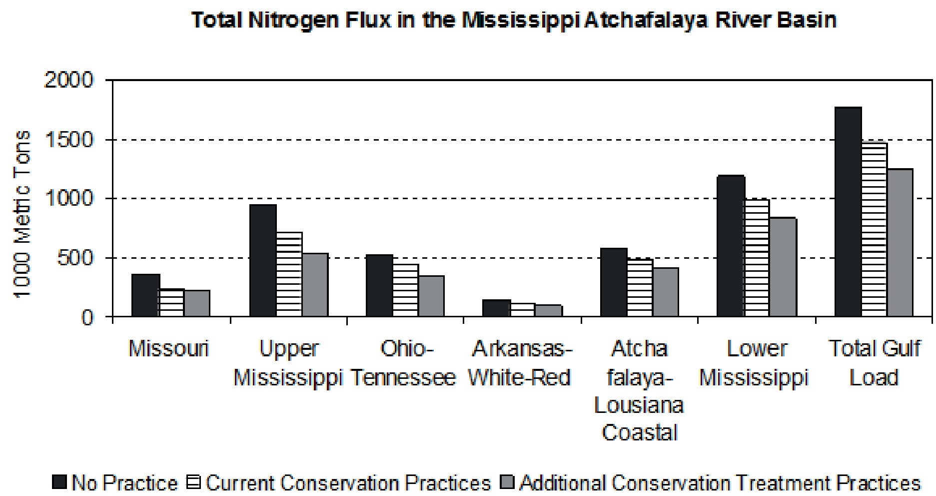

Fig. 5 Nitrogen flux in the Mississippi-Atchafalaya River basin under different conservation practice scenarios.

FUTURE DEVELOPMENTS IN EPIC/APEX

In addition to the incorporation of a pest population model into EPIC/APEX and the elaboration of the spatial weather generator, we are working to include the Southern Oscillation Index (SOI). The SOI is the major driver of the Pacific Ocean's El Nino and La Nina climate patterns which are major factors contributing to worldwide weather variations. An elaboration to the pollution component will include "contaminants of emerging concern" (CECs). CECs are pollutants from both point and nonpoint sources that include both domestic and industrial sources as well as agricultural inputs. CECs affect soil, water and air quality with concomitant impacts on human health and wildlife. Each year approx. 10 000 km^2 of USA land is applied with biosolids and manures of which the majority are used on farmlands for agricultural production. Using an extensive database of soil constituents and new data from soil and water samples for some specific agricultural pollutants (i.e. selenium), APEX is being expanded to model and evaluate a range of salinity ions and heavy metals and other CECs (i.e. hormones). A new database of chemical constituents collected from soils throughout the USA will be incorporated into APEX and expand its growing database. The dynamic and continually evolving APEX tool will provide a resource for management and policy makers to evaluate policy decisions for these pollutants in their efforts to enhance agricultural sustainability, environmental integrity, and ecological services.

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