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Progress and Challenges in Quantifying Water Quality and Ecosystem Responses from Agricultural, Forestry, and Bioenergy Landscapes

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Abstract Global development of the biofuel sector is proceeding rapidly. Biofuel feedstock continues to be produced from a variety of agricultural and forestry resources. Large-scale feedstock production for biofuels could change the landscape structure and affect water quantity, water quality, and ecosystem services in positive or negative ways. With rapid advancements in computation technologies and science, field- and watershed-scale models have become a vital tool for quantifying water quality and ecosystem responses to bioenergy landscape and management practices. This paper presents a brief review of the development and application of field- and watershed-scale models in quantifying water quality and management practices and then discusses a number of critical issues associated with applying these models. In conclusion, the paper identifies specific areas that need improvement and new capabilities for currently used models and addresses challenges in enhancing existing models or developing more sophisticated new models.

Keywords Field-scale models · Watershed-scale models · Water quality · Ecosystem responses · Management practices · Quantification

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Introduction

Increasingly, the USA and other countries are seeking biofuels as a clean, domestic source of energy and as alternatives to fossil fuels. The 2007 Energy Independence and Security Act (EISA) mandated aggressive biofuel production targets for the USA [1]. The EISA calls for the production of 36 billion gallons (BG) of biofuels by 2022, of which 15 BG is corn ethanol and 21 BG is "advanced biofuel." These biofuels could be produced from a variety of crops, ranging from existing crops like corn, soybean, canola, and poplar trees to monocultures or polycultures of perennial grasses and flowers. The latest research suggests that choices between these different bioenergy cropping systems could change the structure of the landscape and affect water quality and ecosystem services in positive or negative ways. For example, modern production techniques have facilitated tremendous gains in crop yields. However, these increases in yields have relied heavily on the intensive use of fertilizer and pesticides, which have polluted some ground and surface waters (http://water.usgs.gov/nawqa).

Agriculture is currently responsible for 76 % of the nitrous oxide (N_2O) generated within the USA and is a large source of nutrient and pesticide runoff to water bodies [2]. Nutrient runoff, particularly reactive nitrogen such as nitrate (NO_3^-), can lead to eutrophication and ultimately to hypoxic (dissolved oxygen <2 mg/L) conditions in water bodies. The National Rivers and Streams Assessment (NRSA) found that in the Midwest, 54 % of stream length was either in poor or fair condition relative to total phosphorus, and 71 % was in poor or fair condition for total nitrogen concentrations [3]. The major concern for surface water polluted with nitrogen and phosphorous is the promotion of algal growth accompanied by aquatic oxygen depletion, fish mortality, clogged pipelines, and reduced recreational values.

The hypoxic zone in the northern Gulf of Mexico occurs annually as a result of, in large part, nutrient inputs from over-fertilization and livestock operations [4]. Rapid declines in the populations of grassland bird species due to habitat loss have been observed in the western Corn Belt. Conversion to agricultural use has also drained native wetlands, with impacts on both breeding and wintering habitat and decreased flood mitigation and buffering capacity. As an alternative to corn, woody or herbaceous perennials could be planted on marginal land to produce bioenergy. Evidence suggests that planting marginal cropland with perennial habitats could increase bird diversity, provide habitat for predators of crop pests, reduce pest problems, and create riparian buffers that remove nutrients from runoff [5]. In sum, all of this evidence suggests that bioenergy production will profoundly affect agricultural and forestry landscapes. The impacts on bioenergy of changes in landscape include effects on water quality and effects on ecosystems and species within them.

Science-based field and watershed models have been widely applied to quantify projected changes in water quality and aquatic ecosystem in response to landscape changes for bioenergy. Field and watershed models are useful tools to interpret, quantify, and assess complex natural processes on the bioenergy landscape, such as surface runoff resulting from precipitation, erosion of upland soil, sedimentation, and contamination of runoff from naturally produced or human-produced chemicals. The models are also useful for evaluating alternative land uses (changes) and best management practice (BMP) impacts, as well as toward solving or alleviating potential problems, such as water quality and adverse ecosystem impacts, which are critical when considering bioenergy development.

To date, numerous field- and watershed-scale modeling studies have been conducted to assess sustainable bioenergy solutions by primarily using a few of the more popular models. Not all of the modeling studies are satisfactory—at times, models do not perform as expected. A question often asked is “was the right model selected?” In fact, selecting the most suitable model is a challenging task. Most of the commonly used models were formulated and developed for use by researchers and scientists. Some models are based on simple empirical relationships having robust algorithms, and others use physically based governing equations generally having computationally intensive numerical solutions. Simple models are often incapable of giving desirable detailed results, while detailed models can be inefficient or prohibitive for complex watersheds. Therefore, a clear understanding of the models, including their capabilities and limitations, is critical in selecting the most suitable model, utilizing its maximum potential, and avoiding any misuse.

The primary goal of this paper is to address the scope of quantifying and evaluating water quality and ecosystem services (including the progress in, need for, concerns about, challenges associated with, and expectations of modeling), in conjunction with the bioenergy landscape, through reviewing available models and providing insights into the theoretical basis, levels of sophistication, and relative accuracies of these models. The compilation of such key field and watershed modeling information associated with bioenergy landscape is expected to help researchers and industry to better understand their options and to make the best choices.

Field and Watershed Models Commonly Used for Simulating Bioenergy Landscape

Increasing interest in bioenergy development has resulted in applying science-based field and watershed-scale models for a number of important sustainability assessments, including quantifying nonpoint source pollutant exports from bioenergy landscape and their source areas and predicting the effects of climate and land use change on water quality and ecosystem. These models have been used for creating the scientific basis for management and policy decisions regarding bioenergy development. Field- or watershed-scale models must include the following components for simulating bioenergy landscape: hydrology, sediment and nutrient transport and fate, and vegetation growth cycle. Among these, some models provide capabilities for simulating best management practices, such as the simulation of a riparian buffer. An extensive review of categories of watershed and water quality models has been conducted by several authors [6–8]. Our focus here is specifically on public domain models that have been applied for simulating bioenergy landscape.

Three models—the Agricultural Policy/Environmental eXtender (APEX) model, the Riparian Ecosystem Management Model (REMM), and the Soil and Water Assessment Tool (SWAT)—were identified as strong bioenergy landscape modeling tools. The models were also chosen to represent simulation capabilities across a range of landscape scales. These three models were considered to have strengths in their simulation of bioenergy feedstocks, management practices, and associated water quality effects. The components and capabilities of these models are similar, but the spatial scales simulated by them are largely different. All of the models selected have a relatively broad user base for their intended applications, ensuring that they are likely to experience continued improvements in the future. Each of these models will be discussed in this paper, including more specific rationales, their key capabilities, and attributes relative to the bioenergy landscape. The physical bases of the models are compiled in Table 1; this information may be helpful in determining the problems, situations, or conditions for which the models are most suitable; their full potential uses and limitations; and the directions for their enhancements.

APEX

The APEX model was developed by the Texas A&M University’s Blackland Research and Extension Center in

Table 1 A summary of APEX, REMM, and SWAT models

Model	APEX	REMM	SWAT
Spatial scale	Field/small watershed	Field	Watershed
Computational unit	Subarea	Zone	Hydrologic Response Unit (HRU)
Runoff/infiltration	Curve number, Green-Ampt	Green-Ampt	Curve number, Green-Ampt
Subsurface flow	Partitioning of excess soil layer water between quick return flow to channel and subsurface lateral flow	Darcy's equation	Kinematic storage and groundwater flow
Groundwater	Computed as a function of groundwater storage	None	Empirical relations
Runoff in channel	Complete flood routing method with and daily and short time interval	None	Variable storage or Muskingum with Manning's equation
Overland sediment	Universal Soil Loss Equation (USLE), MUSLE, RUSLE	USLE	Modified Universal Soil Loss Equation (MUSLE)
Channel sediment	Bagnold's stream power equation with deposition and resuspension allowed	None	Bagnold's stream power equation with deposition and resuspension allowed
Soil nutrient cycles	Carbon, nitrogen, and phosphorous cycles	Carbon, nitrogen, and phosphorous cycles	Nitrogen and phosphorous cycles
Channel water quality	Organic nitrogen, ammonium, nitrate, organic and inorganic phosphorous, algae, CBOD, DO, and pesticides are simulated	None	Organic nitrogen, ammonium, nitrate, organic and inorganic phosphorous, algae, CBOD, DO, and pesticides are simulated
Plant growth	Heat unit approach	Heat unit approach	Heat unit approach
BMP	Planting, harvest, irrigation, fertilization, pesticide, tillage, grazing, mowing	Planting, harvest, irrigation, fertilization	Planting, harvest, irrigation, fertilization, pesticide, tillage, grazing

Temple, Texas [9–11]. APEX is a flexible and dynamic tool that is capable of simulating a wide array of management practices, cropping systems, and other land uses across agricultural landscapes, including whole farms and small watersheds. The model consists of 12 major components: climate, hydrology, crop growth, pesticide fate, nutrient cycling, erosion-sedimentation, carbon cycling, management practices, soil temperature, plant environment control, economic budgets, and subarea/routing. Groundwater and reservoir components have been incorporated in APEX, in addition to the routing algorithms. The routing mechanisms provide for evaluation of interactions between subareas involving surface runoff, return flow, sediment deposition and degradation, nutrient transport, and groundwater flow. Water quality in terms of soluble and organic nitrogen, soluble and organic phosphorus, and pesticide losses may be estimated for each subarea and at the watershed outlet.

The APEX model can simulate extensive BMPs for whole farm (small watershed) management, considering sustainability, erosion (wind, sheet, and channel), economics, water supply and quality, soil quality, plant competition, weather, and pests. Management capabilities include irrigation, furrow diking, buffer strips, terraces, fertilization, manure management, crop rotation and selection, cover crops, biomass removal, pesticide application, grazing, and tillage. The APEX model can be configured for novel land management strategies, such as filter strip impacts on pollutant losses from upslope crop fields, intensive rotational grazing scenarios depicting movement of cows between paddocks, vegetated grassed waterways in combination with filter strip impacts, and land application of manure removed from livestock feedlots or waste storage ponds.

The APEX model has proven to be a useful tool for evaluating complex landscape and management scenarios for farm fields and small watersheds [12]. An integrated APEX model within SWAT has been applied extensively in the evaluation of agricultural management on farms and small watersheds. The APEX model complements the weakness of SWAT well by providing a means of simulating field-level or landscape-level cropping systems, field operations, conservation practices, and silvicultural practices in much more detail than is possible in a SWAT-only simulation. The output from the APEX simulations can then be incorporated into a larger SWAT watershed application, which preserves the accuracy of the APEX simulations in the overall watershed-scale assessment.

REMM

The REMM was developed by the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) in Tifton, Georgia, to quantify water quality benefits of riparian buffers through simulations of surface and subsurface water, sediment, nutrients cycling, and vegetative growth in riparian buffer systems [13]. REMM is conceptually based on the three-zone buffer system. It is a field-scale, process-based model, which simulates interactions among hydrology, vegetation growth and development, sediment transport, and nutrient dynamics. REMM takes upland inputs and computes loading of water, sediments, carbon, and nutrients into the buffer where water, sediments, and nutrients are transported from upland to zone 3 (field edge); zone 3 to zone 2 (mid-buffer); zone 2 to zone 1 (near the stream); and finally from zone 1 to stream via surface runoff, seep flow, and subsurface flow.

REMM simulates three subsurface soil layers that are individually parameterized by the user. A litter layer is included at the surface. Infiltration within the riparian is simulated by using a modified Green-Ampt equation. Subsurface lateral movement of water over an impeding soil horizon is computed by using Darcy's equation. Soil erosion is simulated by using the Universal Soil Loss Equation (USLE). The fraction of sand, silt, clay, small aggregate, and large aggregate particle size classes at the point of detachment is determined by using the Foster approach. In REMM, water quality transport across the buffer is a function of soil deposition, surface runoff and infiltration, adsorption to organic matter in litter and soil, width of the buffer relative to the width of the draining field, vegetation cover of the buffer, slope relative to the draining field, and storm intensity. The REMM simulates vegetation growth and interactions with hydrological and nutrient cycles.

SWAT

SWAT is a public domain watershed model developed by the USDA-ARS. The details of SWAT model used are kept to a minimum here because it is well documented elsewhere in peer-reviewed scientific literature (e.g., [14–16]). In SWAT, the watershed is delineated into a number of subbasins based on topography. Each subbasin possesses a geographic position in the watershed and is spatially related to adjacent subbasins. Each subbasin is further divided into hydrological response units (HRUs) based on land use, soil, and slope classes. HRUs are the smallest computational units in SWAT with unique land use, soil type, and slope within a subbasin. Thus, SWAT can take two levels of the spatial heterogeneity into account. The first level (subbasin) supports the spatial heterogeneity associated with hydrology, and the second level (HRU) incorporates the spatial heterogeneity associated with land use, soil type, and slope class. Within a subbasin, SWAT does not retain the spatial location of each HRU. Hydrologic, soil, water quality, and other processes are modeled within the subbasins through the use of HRUs. Flow generation, sediment yield, and pollutant loadings are summed across all HRUs in a subbasin, and the resulting flow and loads are then routed through channels, ponds, and/or reservoirs to the watershed outlet. All model calculations are performed on a daily time step.

Major model components include climate, hydrology, erosion and sedimentation, nutrient cycle, plant growth, and land management. For climate, SWAT uses the data from the station nearest to the centroid of each subbasin. The hydrological model is based on the water balance equation in the soil profile, where the processes simulated include surface runoff/infiltration, evapotranspiration, lateral flow, percolation, and return flow. SWAT considers a shallow unconfined aquifer, which contributes to the return flow and a deep confined aquifer acting as a source or sink. Surface runoff volume and infiltration are computed by using the modified SCS curve number method or Green and Ampt equation. The peak rate component uses Manning's formula to determine the watershed time of concentration and considers both overland and channel flow. Groundwater flow contribution to total stream flow is simulated by routing a shallow aquifer storage component to the stream [17]. Channel routing is simulated by using either the variable-storage method or the Muskingum method; both methods are variations of the kinematic wave model.

Erosion and sediment yield are estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE). The SWAT model also calculates the contribution of sediment to channel flow from lateral and groundwater sources. The channel sediment routing uses a modification of Bagnold's sediment transport equation [18] that estimates the transport concentration capacity as a function of velocity. The model either deposits excess sediment or re-entrains sediment through channel erosion, depending on the sediment load entering the channel. The delivery ratio is estimated for each particle size as a linear function of fall velocity, travel time, and flow depth.

SWAT simulates the transformation and movement of nitrogen and phosphorus in several organic and inorganic pools. The soil nitrogen cycle is simulated by using five different pools—two are inorganic forms (ammonium and nitrate), while the other three are organic forms (fresh, stable, and active). The SWAT model simulates movement between N pools, such as mineralization, decomposition and immobilization, nitrification, denitrification, and ammonia volatilization. Other soil N processes—such as plant uptake, N fixation by legumes, and nitrate movement in water—are also included in the model.

Nitrates are removed from soil with surface and subsurface runoff, while the amount of organic N transported with sediments is calculated as a function of organic N in the top soil layer and the sediment yield. The loading function estimates daily organic nitrogen runoff loss on the basis of the concentrations of constituents in the top soil layer, the sediment yield, and an enrichment ratio. Nitrate export with runoff, lateral flow, and percolation are estimated as products of the volume of water and the average concentration of nitrate in the soil layer. Once N enters channel flow, the SWAT model partitions N into four pools: organic N, ammonium, nitrite, and nitrate. The SWAT model simulates changes in N that result in movement of N between pools. SWAT simulates six different pools of phosphorus in soil—three are inorganic forms and the rest are organic forms. Transformations of soil P among these six pools are regulated by algorithms that represent mineralization, decomposition, and immobilization. The solution (labile) pool is considered to be in rapid equilibrium (days to weeks) with active pools that subsequently are considered to be in slow equilibrium with stable pools. The amount of soluble P removed in runoff is predicted by using labile P concentration in the top soil layer, the runoff volume, and a phosphorus soil-partitioning factor. Sediment transport of P is simulated with a loading function similar to the organic N transport. In-stream P dynamics in SWAT are also simulated by using two state variables as inorganic and organic P adopted from the QUAL2E model [19].

Similar to APEX, the plant growth module included in SWAT is a simplification of the “Environmental Policy Impact Climate” (EPIC) crop growth module [20], which was developed to support assessments of soil erosion impacts on soil productivity for soil, climate, and cropping conditions representative of a broad spectrum of U.S. agricultural production regions. SWAT uses EPIC concepts of phenological plant development based on daily cumulative heat units; harvest index for partitioning grain yield; Monteith’s approach for potential biomass production; and water, nutrient, and temperature stress adjustments.

SWAT computes plant development on the basis of plant-specific parameters included in the plant growth database. Plant growth is limited by temperature, water, and nutrient deficiencies and is influenced by agricultural management (e.g., fertilization, irrigation, and timing of operations). Crop yield is determined from the biomass at harvest and the harvest index. The ArcSWAT interface enables the simulation of simultaneous use of the SWAT and APEX models. SWAT or integrated SWAT with APEX has been widely applied for quantifying water quality responses from bioenergy landscape and proven to be a useful tool for evaluating a large river basin (e.g., [15, 21]).

Future Bioenergy Landscape Challenges and Model Improvements

Biofuels can be produced from a variety of land uses, ranging from conventional starch-based crops, oil seeds, agricultural residue corn stover, perennial grasses, short rotation woody crops, and forest wood residue to algae. The U.S. Department of Energy (DOE) made an extensive effort to address the environmental sustainability of the bioenergy feedstock supply for the bioenergy and bioproducts industry. In a biomass resource assessment commissioned by DOE, U.S. biomass feedstock potential nationwide was estimated in great detail [22]. The report examines the nation’s capacity to produce a billion dry tons of biomass resources annually for energy uses without impacting other vital U.S. farm and forest products, such as food, feed, and fiber crops. The study provides industry, policymakers, and the agricultural community with county-level data and includes analyses of current U.S. feedstock capacity and the potential for growth in crops and agricultural products for clean energy applications.

Subsequent studies have been conducted to evaluate the impacts of the projected future growth on regional water quality and hydrology in the tributaries of the Mississippi river basin [23–30]. Recent effort focuses on a strategy of incorporating landscape design and management concepts into bioenergy feedstock production by applying conservation practices and land use decisions.

The U.S. DOE has set a goal to validate landscape design approaches for two bioenergy systems that increase land use efficiency and maintain ecosystem and social benefits by 2022 [31]. With this approach, bioenergy feedstock production provides an opportunity for society to create multi-functional landscapes that produce food and energy while supporting environmental quality and ecosystem services. For example, riparian buffers of fast-growing trees and perennial grasslands could be planted along waterways. These buffers could reduce surface runoff into streams, increase water quality, and provide corridors that allow wildlife to move between patches of forest. Ha and Wu [32] recently examined the effect of implementing riparian buffers and converting low-productivity land to switchgrass on nutrients and suspended sediments and hydrology in the watershed of the South Fork Iowa River in Iowa by using a SWAT model. The study found that SWAT represents field buffer and riparian buffer well with its respective sub-modules. Simulation results revealed a significant effect of switchgrass buffer area coverage on nitrogen, phosphorus, and sediment loadings at the watershed. A further low-productivity land conversion to switchgrass by 15.2 % could yield a reduction of suspended sediment, total nitrogen, total phosphorus, and nitrate loadings by 69.3, 55.5, 46.1, and 13.4 %, respectively. Conventional tillage could be replaced with no-till systems and cover crops could be used more extensively, supporting predatory insects and spiders that control pests, thereby reducing erosion and improving soil quality. In the long term, creating sustainable bioenergy landscapes could increase the productivity of agriculture by supporting crop pollination and natural pest control, in addition to supporting a variety of other services that have value beyond production.

Ecosystem services are the multitude of benefits humans receive from the resources and processes supplied by natural and managed ecosystems. Therefore, a major challenge of bioenergy and natural resource use and management is fulfilling multiple and sometimes conflicting demands for agricultural goods, water quality, and ecosystem service for the benefit of all. Key to overcoming this challenge is identifying pollutants of concern and the relative role of point and non-point pollutant sources, strategizing pollution prevention and control measures, and tracking progress and making adjustments toward meeting overall watershed goals. In that context, the USA is focusing on the "watershed approach," in association with the U.S. EPA's Total Maximum Daily Load (TMDL) program. A watershed approach also highlights cost-effective opportunities to go beyond reducing polluted runoff and water quality pollution and protecting water sources by, instead, providing ways to think about how to enhance the overall health of the watershed ecosystem and preserve biodiversity.

The three models (APEX, REMM, SWAT) discussed above are promising tools to conceptually simulate watershed and land use-related change and ecosystem response, but additional work is needed to allow these models meet future challenges for use in sustainable landscape studies. APEX, REMM, and SWAT are useful for analyzing long-term effects of hydrological cycle, land use changes, and management practices (especially agricultural practices) on the bioenergy landscape. APEX is best suited for a field or small watershed scale, REMM is designed specifically for riparian zone simulation, and SWAT is best suited for a large river basin. Because daily time steps are used, these models do not simulate storm events adequately. The advantages of APEX are that field units within APEX have spatial relationships and can be routed within a subbasin. APEX simulates multiple cropping, detailed management practices related to farm animal productions, impacts of BMPs, and wind erosion, all of which are not currently possible with the SWAT model. SWAT also cannot track the spatial distribution of HRUs in a subbasin, which is one of a few weaknesses in simulating landscape processes. There is a need to improve the plant growth module included in these three models for simulating physically based plant dynamic cycles.

Vegetated riparian buffer zones established between agricultural fields and receiving waters have long been recommended as a BMP to reduce the amount of sediment, nutrients, and pesticides entering water bodies [33]. The ecological health of rivers is an integrated measure of the landscapes that they drain. However, all currently used field and watershed models (including APEX and SWAT) are weak in simulating riverine systems and riparian zones in the watershed. Although the REMM can be applied to a riparian zone for analyzing riparian buffers within the watershed, estimates of water, sediment, and water quality at stream sections or watershed outlets cannot be simulated as a result of a lack of integration mechanisms. Therefore, integrating REMM into APEX and SWAT to facilitate the simultaneous use of the REMM and APEX or SWAT will improve the current capabilities of field and watershed models and better characterize the effectiveness of BMP implementation.

In the future, SWAT is also required to enhance the simulation of surface and subsurface flow and nutrient and pesticide transport for landscapes. In addition, the science linking stressors (e.g., pollutants, land use conversion, and hydrologic modification) to ecosystem responses has not been fully developed and included in models. This limitation poses a significant challenge for using ecosystem indicators within the bioenergy program. The complexity of landscape ecosystems and the great spatial and temporal variability of the factors that control the system have thwarted efforts to develop a comprehensive mechanistic watershed model for predicting ecosystem responses in a complex landscape system.

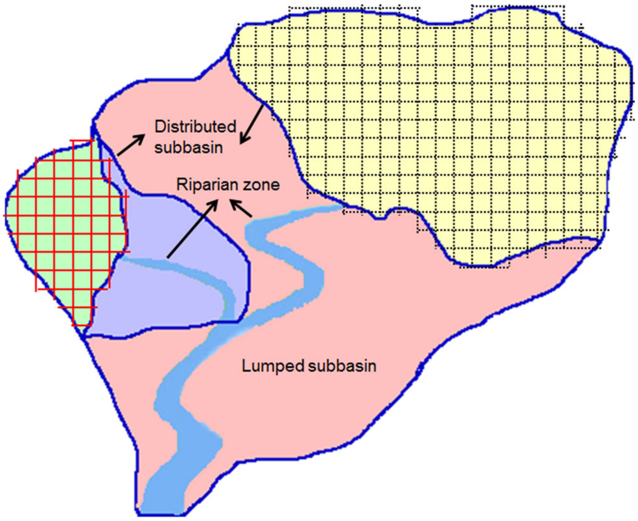

Fig. 1 A conceptual watershed site model

Additional future modeling needs for simulating ecosystem factors include the development of (1) metrics that link ecosystem service community characteristics with individual pollutants, (2) an integrated assessment methodology based on multiple biological community types, and (3) biological criteria-based water quality standards. A 2D hydraulic model has been developed and released within HEC-RAS version

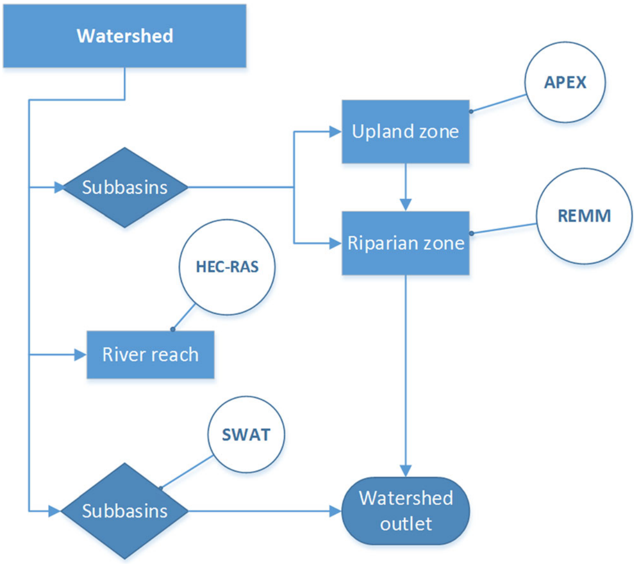

Fig. 2 A framework for an integrated field, riparian, riverine and watershed model

5.0 (http://www.hec.usace.army.mil/software/hec-ras/). An updated HEC-RAS-2D model will include capabilities to simulate the transport and fate of nutrients in riverine and floodplain systems and the interactions of water quality with the riparian vegetation cycle under varying site conditions. A future goal is to directly link this tool to the watershed models discussed above, a strategy that will help overcome the weakness of current watershed models and improve the prediction of water quality and riparian vegetation outcomes. A conceptual site model for the watershed system is illustrated in Fig. 1. A comprehensive modeling framework for simulating complex bioenergy landscape is given in Fig. 2. The integration of SWAT with REMM, APEX, and HEC-RAS would improve the assessment of bioenergy landscape and management scenarios, which is vital to a comprehensive watershed management.

The above discussion about the needed improvements to models is by no means complete. It can, however, provide a basis for expanding other modeling capabilities. It may also serve to (1) determine the problems, situations, or conditions for which the models would be most suitable; (2) define likely the accuracies and uncertainties; (3) determine their full potential uses and limitations; (3) determine the direction for enhancing them by combining each model's strengths; and (4) identify new developments.

Summary and Conclusions

Field and watershed models play a central role in the bioenergy landscape and assessment of water quality. Models are the means of making predictions—not only about the adoption of landscape design options including BMPs and land conversion to achieve water quality standards but also about the effectiveness of different approaches in modifying relevant environmental stressors to conserve soil, water, and wildlife quality, in order to meet the requirement of eco-services and achieve a designated use. Before a model or modeling system is used as an evaluation tool, its credibility must be established. Therefore, this paper is intended to provide an important review and aid in the understanding of currently used models in evaluation and application efforts.

This paper underscores that three field- and watershed-scale models (e.g., APEX, REMM, and SWAT) have proven to be robust bioenergy landscape assessment tools for many types of land use changes and land management and water quality applications. These models are useful for long-term simulations and assessments of agricultural, forestry, and bioenergy landscapes. SWAT has been proven to be an effective tool for large watershed applications. The APEX model is only suitable at small watershed and field scales. REMM is suitable for studying study riparian buffer zones and evaluating riparian management practices. All of these models are based on empirical relations and physically based principles with varying degrees.

In spite of their effectiveness, the models have considerable gaps that limit their use of as a comprehensive landscape assessment tool. There is also a need to expand these three models to provide evaluations of critical ecosystem service issues, such as assessments of the effects of the land use changes on the habitats of many resident and migratory species. Ecosystem service aspects on the landscape present further challenges the capabilities of these models, which reinforce the need for further research on and development of these three models.

Integrated APEX, REMM, and SWAT models with a robust riverine hydraulic, sediment and water quality model like HEC-RAS are the best choice to quantify water quality and ecosystem responses from a bioenergy landscape for large river basins, and the integrated models could be used as a "management tool." The primary advantage of using integrated models is to enable a realistic representation of the landscape and transport processes, instead of the eclectic and ad hoc conceptual representations used by individual models.

Compliance with Ethical Standards

Conflict of Interest Zhonglong Zhang and May Wu declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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