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Review papers

Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: A systematic review

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SUMMARY

SWAT, a watershed modeling tool has been proposed to help quantify ecosystem services. The concept of ecosystem services incorporates the collective benefits natural systems provide primarily to human beings. It is becoming increasingly important to track the impact that human activities have on the environment in order to determine its resilience and sustainability. The objectives of this paper are to provide an overview of efforts using SWAT to quantify ecosystem services, to determine the model's capability examining various types of services, and to describe the approach used by various researchers. A literature review was conducted to identify studies in which SWAT was explicitly used for quantifying ecosystem services in terms of provisioning, regulating, supporting, and cultural aspects. A total of 44 peer reviewed publications were identified. Most of these used SWAT to quantify provisioning services (34%), regulating services (27%), or a combination of both (25%). While studies using SWAT for evaluating ecosystem services are limited (approximately 1% of SWAT's peered review publications), and usage (vs. potential) of services by beneficiaries is a current model limitation, the available literature sets the stage for the continuous development and potential of SWAT as a methodological framework for quantifying ecosystem services to assist in decision-making.

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1. Introduction

Ecosystem Services (the benefits humans derive from nature; ES) have become a central issue in environmental management and policy making (MA, 2005). The concept of ecosystem services has been broadly defined by Daily (1997) as ecological functions that sustain life, and has been classified into four types of services (provisioning, regulating, supporting, and cultural). Yet, this concept is not operational unless placed within geographical context and by specifying the ecosystem characteristics and services of interest (Fisher et al., 2009). Given the intensified degradation of the environment (expected as a consequence of the growing demand for goods and benefits) it is likely for ecosystems to be modified to the extent that they can no longer render services to support life in the near future (Foley et al., 2005). Hence, our understanding of ecosystem functioning will be challenged and we will be required to better integrate the supply–demand chain to reduce potential negative tradeoffs and conserve keystone ES. Among the Millennium Ecosystem Assessment (MA) findings, four major conclusions were made in terms of the future challenges of ES. First, through the analysis of an extensive body of evidence, scientists agreed that a majority (60%) of the examined ES are being degraded. Second, changes in ES often occur in accelerated (i.e. disease emergence) or abrupt (i.e. floods) episodes. Third, dryland ecosystems represent the most vulnerable environment for maintaining viable ES for human well-being. Fourth, nutrient loading of ecosystems is a significant and increasing threat to environmental health. Along with these challenges, there are many knowledge gaps on how to approach these issues. ES modeling could help address some of these concerns, as it can assist in the anticipation of consequences of changes made to ecosystems in terms of the services provided to humans (Vigerstol and Aukema, 2011).

To help quantify ES processes, modeling tools are being developed and implemented to integrate many components that make up natural and human modified landscapes, as well as society's impact on them (Bagstad et al., 2013a). Past research has focused on valuing ES from an anthropogenic perspective and through economic models (Costanza et al., 1997; Guo et al., 2000; Chan et al., 2006; Naidoo and Ricketts, 2006; Anderson et al., 2009). More recently, the growing need for understanding ecosystem processes and their continuous supply of benefits has led scientists to develop modeling tools that can assess the supply of ES in addition to their capital value. Among some of the emerging tools for quantifying ES are the Multi-scale Integrated Model of Ecosystem Services (MIMES), the ARtificial Intelligence for Ecosystem Services (ARIES), the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), Co$ting Nature, and the reconceptualized application of the Soil and Water Assessment Tool (SWAT) (Boumans et al., 2015; Mulligan, 2015; Gómez-Baggethun et al., 2014; Bagstad et al., 2013b; Arnold et al., 1993). While these tools require different inputs and integrate ecosystem and socio-economic processes through distinct approaches, they find commonality in that they attempt to simulate the effect of development and land management over natural, human, and built capital systems.

Depending on the information required, spatially explicit hydrological models could be broadly used as practical tools to quantify ES and identify their providing units in the landscape (Egoh et al., 2012). With this information it is possible to determine what areas are needed to be protected and restored to ensure adequate ES levels (Quintero et al., 2009). The integrated assembly characteristic of hydrological models combining vegetation, soil, water, management, and weather components of landscapes, serves as a comprehensive approach to estimate several variables that can be interpreted as ES. Water flow and hydrological processes in general, are easier to model than more abstract ES (e.g. aesthetic appreciation). Hence, interest has been placed on expanding the utility of hydrological modeling tools to conduct ES assessments (Vigerstol and Aukema, 2011). Furthermore, water provisioning and water flow stability are ES not only significant to natural resource management, but scarcity and reduced accessibility could cause future social conflicts that could transcend political boundaries and turn into global warfare (Zeitoun and Warner, 2006; Gleick, 1993). Modeling the provisioning of water related resources has become a central theme in ES management (Galvan et al., 2013; Liersch et al., 2013; Welderufael et al., 2013; Jayakrishnan et al., 2005).

SWAT has been proposed as a mechanism to help quantify ES in watersheds (Vigerstol and Aukema, 2011). As a hydrological model, SWAT has been used at various temporal scales to simulate plot size as well as continental watersheds (Radcliffe et al., 2015; Jayakrishnan et al., 2005). Given its open access policy and detailed documentation, the application of the model has been successful and extensive (Krysanova and White, 2015). Its multiple input parameters and process-based biogeochemical submodels, strengthens the model's applicability to simulate not only water flow dynamics, but also estimate several water quality and plant growth variables that can be used in the assessments of land and agricultural management impacts on ES (Galvan et al., 2015; Arnold et al., 2012a). SWAT studies include the analyses on nutrient and sediment transport related to best management practices, wetlands, irrigation, bioenergy crops, climate change, land use change and others (Krysanova and White, 2015). Furthermore, compared to other environmental modeling tools, the proper calibration of SWAT can serve as an effective approach to help evaluate nutrient loading (Radcliffe et al., 2015; Golden et al., 2014; Vigerstol and Aukema, 2011), which is one of the MA described ES future challenges. Yet, it is not clear what is the model's potential for simulating more abstract ES and flows.

Vigerstol and Aukema (2011) provide an initial guideline on how and when to use SWAT (in addition to three other modeling tools: VIC, InVEST, and ARIES), as a way to address ES questions. Such studies reflect the growing interest on the application of SWAT as a tool for quantifying ES and estimating the consequences of management impacts. Here we examine the literature where SWAT has been used in combination with the concept of "Ecosystem Services" either in an experimental or theoretical manner. We describe the application of SWAT to estimate provisioning, regulating, supporting and cultural ES. Our objective was to compile the available knowledge on the application of SWAT for addressing ES issues, and further identify ways in which this tool could be used to provide science-based evaluations for policy and decision making.

2. Methods

The existing literature was reviewed to identify research articles where SWAT has been used to conduct biophysical and/or socio-economic assessments of ES. The database server Web of Science was initially consulted. In addition, we used SWAT's Literature Database for Peered Reviewed Journals hosted by the Center for Agricultural and Rural Development at Iowa State University (www.card.iastate.edu/swat_articles). The terms "SWAT" and "Ecosystem Services" were used as search concepts. Publications containing these two terms were reviewed and described to identify application patterns, understand the quantification of ecosystems services, and the usage of SWAT as a tool that can help in decision making for natural resource management and policy. The literature review enabled the identification of five aspects of the studies based on expert judgment to accommodate our research objectives: (1) ES; (2) Broad Implications; (3) Location (where the study took place); (4) SWAT Output Variables; and (5) ES Category. Given the relatively low number of publications when combining the search terms, we did not conduct statistical analyses of the results. Instead, we comprehensively compare them in a descriptive manner.

3. Results

3.1. General overview

As of July 15, 2015 the online database Web of Science search for peered reviewed publications using the acronym "SWAT" resulted in a total of 2088 publications. In contrast, the ecological concept of "Ecosystem Services" resulted in 8554 articles (Fig. 1). Together however, the database identified only 33 peered reviewed articles. However, a couple of studies did not referred to the "Soil and Water Assessment Tool" acronym "SWAT" (Qasim et al., 2013; Akhatar et al., 2013).To complement this list, SWAT's Literature Database for Peered Reviewed Journals, which contains a total of 2198 articles, listed a total of 37 papers using both terms. From this list, some studies did not actually engage in developing a SWAT project (Golden et al., 2014; Notter et al., 2012; Johnston et al., 2011). There were 16 studies common to both databases, 8 were unique to Web of Science and 20 were unique to SWAT's Literature Database. From the combined results we identified 44 articles that used SWAT to evaluate or discuss potential ES analyses (Table 1). It is clear that the number of studies on the topic of ES and the implementation of SWAT as a research tool have been rapidly increasing in the last couple of decades (Fisher et al., 2009). In 2014, the number of studies published on the topic of ES and SWAT reached a rate of almost five articles per day, and more than one per day, respectively. Along with greater research interest in this topic and tool, the number of publications using SWAT to evaluate ES has been increasing as well (see Fig. 2). However, SWAT analysis of ES are limited accounting for only 1.5% of SWAT's publications and 0.4% within the topic of ES.

The list of publications within the databases is not comprehensive as it may exclude articles in which SWAT analyses were used to answer ecosystem service inquiries though in a non-explicit manner. Most of the research described (37%) were conducted in the North America, followed by studies in Africa and Asia (26% and 21%, respectively). To a lower extent, the model has been applied in Europe (8%) and South America (5%). Among the articles listed, 29 used SWAT to allude or conduct analysis that measured provisioning services (Fig. 3). From this list, 23 mentioned SWAT analysis of regulating services, three studies explicitly addressed supporting services, and only one study discussed the use of the hydrological model as a tool that can help evaluate a landscape's cultural services (Baker et al., 2015).

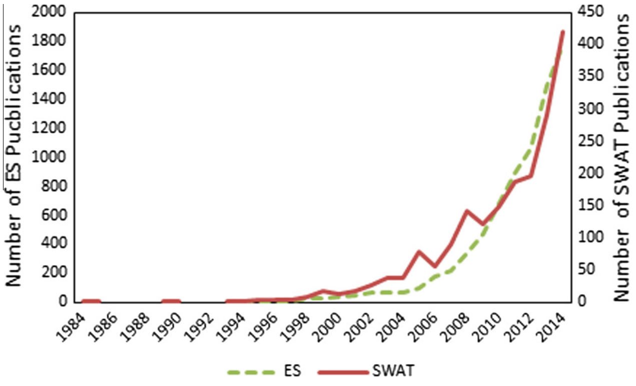

Fig. 1. Distribution of publications using SWAT and Ecosystem Services (ES) over time. Data from 2015 is not shown.

Provisioning and regulating processes are the most common ES evaluated using SWAT. Provisioning services were mainly focused on quantifying fresh water production in watersheds (Fig. 4), and a few (5) used the model to estimate other provisioning services such as crop yield and biomass (Lautenbach et al., 2013; Bekele and Nicklow, 2005). The most common water quantity output in SWAT was stream flow (Fig. 4). Publications evaluating regulating services were primarily interested in analyzing water quality to evaluate water pollution/purification processes (Fig. 4). Water quality was primarily assessed by measuring sediment yield as the most common output variable in SWAT, followed by nutrient loss outputs such as nitrate loading and total nitrogen (Fig. 4). Given that cultural ES imply an understanding of human perceived benefits, it is clearly the least common type of service modeled (Table 1).

4. Discussion

4.1. Calibration parameters and output variables

In addition to SWAT's main input components (soils, elevation, weather, land use), the model contains a series of calibration parameters that can modify these components to represent site-specific watershed conditions (Neitsch et al., 2011). This renders the modeling tool effective at simulating landscape conditions and producing realistic outputs. After calibration and validation, parameters related to vegetation, soil, water, and management components can be further adjusted to simulate potential scenarios to forecast future conditions and/or address ES questions. Among the vegetation inputs, the user can modify characteristics related to the land use by modifying parameters such as the amount of precipitation interception (canopy storage capacity and/or leaf area index), water intake, water evapotranspiration, stomatal conductance, etc. (Qiao et al., 2015). Soil parameters can also be calibrated to represent actual conditions and can be modified to reflect human induced and climate changes in the environment (Post et al., 2008). Various soil hydraulic properties are available to be modified along with physical and chemical characteristics (Arnold et al., 2012a). Parameters such as runoff curve number, ground water delay, and soil evapotranspiration compensation factor, are frequently used for calibration (Arnold et al., 2012b). While default values may be used if characteristics are unknown, it is in the user's interest to develop a robust model with inputs that are as close to reality as possible. This may be a drawback particularly for contexts in which information is not available (Ndomba et al., 2008).

After calibration, the simulation of watersheds in SWAT can produce outputs at different spatial and temporal scales. SWAT can provide data at the watershed, the sub-basin, and at the Hydrologic Response Unit (HRU) level, as well as for impounded areas (ponds, wetlands, etc.), reservoirs, and/or reach geographical features at the average annual, monthly, daily and hourly time frames (Arnold et al., 2012b). These output options allow the user to compare different land use features during different seasons, either depicted or weighted, and in a snapshot or accumulated over time.

Table 1
List of peered reviewed publications that used SWAT as a tool for estimating ecosystem services (ES).

Reference	Ecosystem service	Broad implications	Location	SWAT output variables	Ecosystem service category
Arias et al. (2011)	Sediment Regulation	Hydropower longevity and payment for ES	Cambodia	Sediment Yield	Regulating
Baker et al. (2015)	Water Quantity	Gender landscape perception	Ethiopia	Surface runoff, Actual Evapotranspiration, Shallow Aquifer Storage, Deep Aquifer Storage	Cultural and Provisioning
Bekele and Nicklow (2005)	Water Quality	BMP assessment for optimization	USA	Sediment yield, Phosphorous Load, Nitrate Load	Regulating
Bekele et al. (2013)	Food, Water Quantity, Carbon Sequestration and Flood Regulation	BMP Assessment/tradeoff/ optimization analysis	USA	Crop Yield, Stream Flow, Carbon[a], Nitrate Load, Phosphorus Load, Sediment Yield	Provisioning and Regulating
Caro-Borrero et al. (2015)	Water Quantify and Habitat	Hydrologic structures	Mexico	Water Yield, Lateral Flow, Groundwater Flow, Actual Evapotranspiration	Provisioning
Chiang et al. (2014)	Water Quality	Model calibration	USA	Stream Flow, Total Suspended Sediments, Total Nitrogen	Regulating
Cools et al. (2011)	Water Quality	Model Coupling/Emission Reduction	Belgium	Stream Flow, Total N	Regulating
Fan and Shibata (2014)	Water Quantity	Watershed Management	Japan	Water Yield, Evapotranspiration	Provisioning
Fan and Shiabata (2015)	Water Quality	Watershed Management	Japan	Evapotranspiration, Water Yield, Surface Runoff, Potential Evapotranspiration, Organic N, Organic P, Total N	Provisioning and Regulating
Fukunaga et al. (2015)	Water Quantity	Watershed Management	Brazil	Stream Flow	Provisioning
Garg and Wani (2013)	Water Quantify	Watershed management	India	Surface Runoff, Groundwater Flow, Evapotranspiration	Provisioning
Gathenya et al. (2011)	Water Quantity and Sediment Regulation	Climate and land use change	Kenya	Water Yield, Sediment Yield, Groundwater Flow	Provisioning and Regulating
Gebremariam et al. (2014)	Water Quantity	Hydrological model comparison	USA	Stream Flow	Provisioning
Glavan et al. (2015)	Food, Water Quantity and Quality	BMP Assessment	Slovenia	Potential Evapotranspiration, Actual Evapotranspiration, Soil Water, Percolation, Surface Runoff, Lateral Flow, Water Yield, Organic N, N Fixation, Plant N Uptake, N Leached (NO3L), Biomass	Provisioning and Supporting
Glavan et al. (2013)	Water Quantity	Land use patterns on historical hydrological processes. Crop/ water productivity or blue/green water	Slovenia	Stream Flow	Provisioning
Golden et al. (2014)	Flood Regulation	Hydrological Model comparison	USA	Surface Runoff, Groundwater flow[b]	Regulating
Immerzeel et al. (2008)	Water Quality	Water conservation policies to reduce irrigation and evapotranspiration, PES	Tibet	Water Yield	Provisioning
Johnston et al. (2011)	Water Quantity	Integrated modeling framework for characterizing ES	USA	Stream Flow	Not Applicable
Jujnovsky et al. (2012)	Water Quantity	Watershed Management	Mexico	Water Yield, Surface Runoff, Groundwater flow, Lateral Flow Actual Evapotranspiration	Provisioning and Regulating
Jung et al. (2013)	Water Quantity	Impact of climate change on water availability	South Korea	Stream Flow	Provisioning
Kauffman et al. (2014)	Sediment Regulation and Soil Moisture	BMP Assessment	Kenya	Surface Runoff, Sediment Yield, Plant Transpiration, Soil Evaporation, Groundwater Flow	Regulating
Lant et al. (2005)	Sediment Regulation	Impact of implementation of CRP practices	USA	Sediment Yield	Regulating
Lautenbach et al. (2013)	Food	BMP Assessment /tradeoff	Germany	Stream Flow, Nitrate Load, Crop Yield, Actual Evapotranspiration	Provisioning and Regulating
Liersch et al. (2013)[c]	Water Quantity, Flood Regulation	Watershed management	Niger	Stream Flow	Provisioning
Liu et al. (2013)	Food, Flood Regulation, Water Quality,	BMP Assessment/tradeoff	USA	Stream Flow, Crop Yield, Nitrate Load, Phosphorus Load	Provisioning and Regulating
Logsdon and Chaubey (2013)	Water Quantity, Sediment Regulation, Flood Regulation, Food, Fuel	BMP Assessment	USA	Stream Flow, Total Suspended Solids, Nitrate Concentration, Total Phosphorus,	Provisioning and Regulating

Table 1 (*continued*)

Reference	Ecosystem service	Broad implications	Location	SWAT output variables	Ecosystem service category
Mwangi et al. (2015)	Water Quantify and Sediment Regulation	BMP Assessment	Kenya	Stream Flow, Water Yield, Sediment Yield, Sediment Concentration	Supporting
Norman et al. (2012)	Sediment Regulation and Flood Regulation	Trans-boundary ES assessment	US-Mexico	Water Yield, Sediment Yield	Provisioning and Regulating
Norman et al. (2013)	Water Quantity	Policy decision-making	Mexico and USA	Stream Flow, Groundwater Flow, Actual Evapotranspiration, Sediments Yield, Transmission Losses	Provisioning
Notter et al. (2012)	Water Quantity, Flood Regulation	SWAT-P documentation	Tanzania and Kenya	Effective Water Use, Water Stress, Maximum Plant Evaporation, Actual Plant Evaporation, Flooding	Provisioning and Regulating
Palao et al. (2013)	Sediment Regulation	PES schemes	Philippines	Sediment Yield, Sediment Concentration	Regulating
Palazón et al. (2014)	Sediment Regulation	Erosion Processes	Spain	Sediment Yield, Stream Flow	Regulating
Piman et al. (2012)	Water Quantity	Dam construction impact, Hydroelectric electricity production	India, Burma	Stream Flow	Provisioning
Post et al. (2008)[c]	Carbon sequestration	Changes in C storage in soil due to land use change and climate change	Germany	Surface Runoff, Water Yield, Actual Evapotranspiration, Groundwater Flow, Crop Yield	Provisioning and Regulating
Qiao et al. (2015)	Water Quantity and Habitat	Invasive species and climate change adaptation	USA	Potential Evapotranspiration, Actual Evapotranspiration, Surface Runoff, Soil Water	Provisioning and Supporting
Rodrigues et al. (2014)	Water Quantity	Watershed Management	Brazil	Stream Flow	Provisioning
Roebeling et al. (2014)	Water Quality	Trans-boundary catchment management	Spain and Portugal	Total nitrogen[a]	Regulating
Salmoral et al. (2015)	Water Quantity	Land use and land cover change	Spain	Stream Flow	Provisioning
Secchi et al. (2007)	Water Quality	Carbon sequestration	USA	Sediment Yield, Nitrate Load, Phosphorus Loads	Regulating
Song et al. (2012)	Water Quantity	PES schemes	China	Surface Runoff	Provisioning
Swallow et al. (2009)	Sediment Regulating	Trans-boundary ES assessment/tradeoffs	East Africa	Sediment Yield	Regulating
van de Sand et al. (2014)	Water Quantity and Quality	BMP Assessment, linking PES and adaptation to climate change	Kenya	Stream Flow, Sediment Concentration, Sediment Yield	Provisioning and Regulating
Vigerstol and Aukema (2011)	Water Quantity, Water Quality and Sediment Regulation	Literature review of ecosystem service modeling	Not Applicable	Not Applicable	Not Applicable
Welderufael et al. (2013)	Water Quantity	Land use scenario comparison for water harvesting	South Africa	Stream Flow, Groundwater Flow, Actual Evapotranspiration	Provisioning

[a] Article does not specify what specific SWAT output was used for estimations.

[b] Actual values for outputs were not estimated.

[c] Project uses SWIM model derived from SWAT.

Depending on the research questions, as a deterministic model SWAT can estimate specific output values for a given ES (Welderufael et al., 2013), be used to compare the relative differences among different scenarios (Norman et al., 2012), or analyzed to produce a combination of both (Post et al., 2008). The increasing number of publications using SWAT for ES shows new interests in exploring this capability. These studies demonstrate a variety of ways in which the model can be applied for this purpose. While the outputs currently available in SWAT are limited to water-related ES, given the model's accuracy and customized applicability these could be standardize for the estimation and identifying ecosystem degradation processes occurring worldwide (MA, 2005). In this sense, SWAT could serve as a monitoring tool that could help address some of the new millennium's knowledge gaps.

4.2. Modeling ecosystems services in SWAT

Among the MA future challenges, SWAT can evaluate changes in water quality through the estimation of nutrient loading (MA, 2005). Degradation of water quality is among the most rapid and noticeable ES problems. Of the total number of SWAT publications, 28% studied water quality issues. Most importantly, the model's software is continuously being enhanced to better simulate water quality processes and increase its global applicability (Gassman et al., 2014).

SWAT output variables address various water-related processes in watersheds. As a process-based hydrological model, SWAT's origins were founded on predicting the impact of land management practices on the watershed water balance (Arnold et al., 1993). From that basis, the fate and transport of sediments, nutrients, and pesticides followed, as well as enhanced vegetation and climate processes (Arnold and Fohrer, 2005). While the model was developed to address water quality concerns, among the different ecosystem service categories defined by the MA (2005), SWAT's greatest contribution so far has been measuring provisioning services. Water yields, crop yields, and biomass, are the most common outputs analyzed in SWAT which directly quantify provisioning ES. The proper calibration of SWAT requires (at a minimum) for the

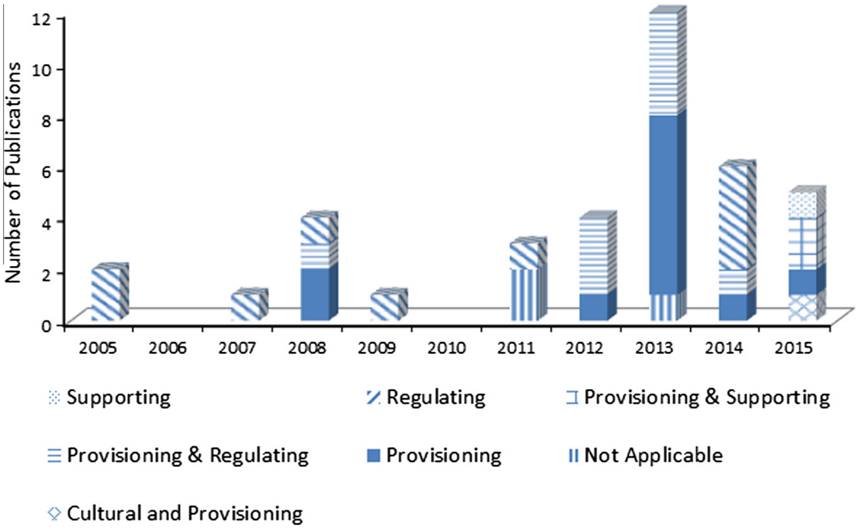

Fig. 2. Publications using SWAT to evaluate different ES over time. Bar patterns indicate the type of ES evaluated or what combination of these (provisioning, regulating, supporting, and cultural).

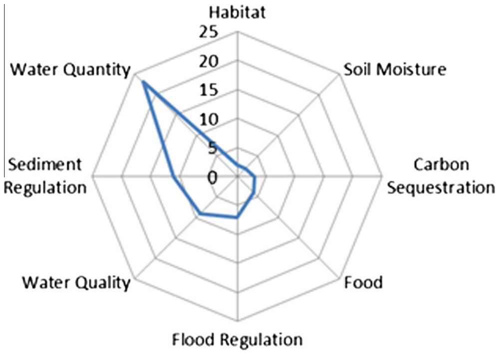

Fig. 3. Radar chart shows the ES topics most frequently address by SWAT publications.

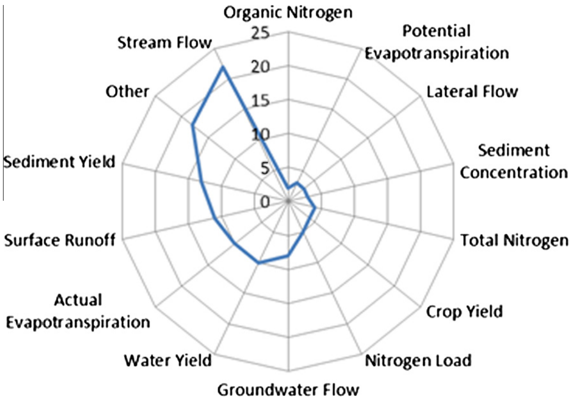

Fig. 4. Most common SWAT output variables used for interpretation of ES. The term "Other" compiles various outputs that individually scored less than 2% of frequency of use.

user to compare observed water flow measurements to the predicted values. Hence, water yield becomes the most common output variable. In the absence of measured flow data, as in many developing countries, the application of SWAT for hydrological or ecosystem service analysis is limited and may result in the comparison of relative values (Ndomba et al., 2008). While not accurate, these relative comparisons could be informative in decision making processes. SWAT's strength lies on modeling hydrological processes (streamflow, surface runoff, evapotranspiration, soil and groundwater), but it can also be used to model vegetation growth by simulating the conversion of plant intercepted light into biomass (Neitsch et al., 2011; Immerzeel et al., 2008). A more robust crop simulation model however would be the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003). In addition to site specific conditions, DSSAT input modules allows the user to include a broader array of species specific characteristics such as phenology, photosynthesis, and nutrient demands, to estimate plant growth (Jones et al., 2003). Yet, DSSAT can only do this for a single crop and within the same biophysical conditions. In spite of poor data availability and depending on the level of information provided by the desired outputs, SWAT has been successful at modeling various provisioning ecosystem services.

Selected supporting services can also be estimated using SWAT. By definition, supporting ES are necessary for the maintenance of ecosystems and the production of all other services (MA, 2005). The process of soil formation, for example, is an ES that supports the production of food and raw materials, and these would fall under the category of provisioning services. On the other hand, the capability of SWAT to produce quantitative data for cultural ES is less clear. Given the nature of cultural ES, these may be intangible benefits people received and perceived from nature in the form of spiritual enrichment, recreation, aesthetics, or cognitive development (MA, 2005) Hence, socio-economic data and not biophysical data are required to estimate these services. Handling socio-economic data constitutes an important limitation of SWAT at the present moment.

While research using SWAT in combination with socio-economic analysis has been done for the purpose of providing more comprehensive research findings, there is no standardized framework. Output variables from SWAT have been used to determine the potential of ecosystems to produce services. These can then be analyzed to assign a market value to ES (Bekele et al., 2013; Arias et al., 2011), to determine the relation between the supply of natural resources and human demand (Jujnovsky et al., 2012), to compare the production of these services with human perception (van de Sand et al., 2014), or to analyze tradeoffs between economic benefits and environmental impact

(Lautenbach et al., 2013). SWAT research that addresses socio-economic aspects, by its own nature, requires a systematic approach that looks at tradeoffs between the production of ES, their impact on other ES (as some relations may be positive, neutral, or negative), their use by human beneficiaries, and the feedback of society' consumption/depletion. While comprehensive studies are difficult to produce, the work by Lautenbach et al. (2013) provides an integrative analysis on the biophysical tradeoffs that exist between bioenergy and food production and their differential impact on water quantity and quality. The work couples SWAT with a multi-objective optimization algorithm (NSGA-II) to produce what they call a "functional near-optimal solution among competing objectives". This type of approach addresses the biophysical tradeoff that exists within provisioning services in a manner that integrates socio-economic objectives and potential implications on renewable energy legislation. Similar to this study, other research has integrated SWAT outputs with socio-economic frameworks (Bekele et al., 2013; Bekele and Nicklow, 2005). In these types of studies, researchers make use of additional tools, algorithms, frameworks, etc. to determine human consumption, monetary, or decision making processes.

SWAT is efficient at modeling the potential production of many ES in situ. However, the model is not yet capable of linking these services with its beneficiaries in a conceptual, systematic, or spatially explicit manner. While there are some features in SWAT that are capable of simulating water consumption for irrigation, urban, or industrial purposes (water use input file), it remains a challenge in SWAT and within ES in general, to model the flows from where services are produced to where they are consumed, as well as feedback loops (Arnold et al., 2012b; Bagstad et al., 2013a; Arnold and Fohrer, 2005). SWAT application can, however, address a large number of issues within natural resource management and decision making such as water conservation, land use change, carbon sequestration, and climate change among others. Perhaps one of the most common broad applications of SWAT as an ES modeling tool is the comparison and evaluation of best management practices, which often look at the tradeoffs between provisioning services, their impact on regulating services, and/or monetary impacts (Mwangi et al., 2015; van de Sand et al., 2014; Logsdon and Chaubey, 2013; Liu et al., 2013). While improvements are made, or other models are developed to help solve these complex issues, SWAT continues to gain strength and momentum in its ability to address multiple ES simultaneously and produce outputs that can easily be coupled with other models or be further analyzed.

4.2.1. Provisioning services

Water yield is the most commonly analyzed SWAT output variable. Water availability for irrigation in agriculture, domestic use, electricity production through dams and hydroelectric plants, and even for recreational and tourism services, can all be analyzed through water yield. In addition, other important provisioning ES variables that can be estimated with SWAT include crop yield and vegetation biomass. These variables can be used to estimate the provision of services such as food production, biofuels, and habitat for wildlife. Logsdon and Chaubey (2013) describe a methodology to measure provisioning and regulating ES using SWAT outputs. They used stream flow, sediment yield, total biomass, total crop yield, among others to measure five distinct provisioning and regulating ES that include freshwater, food, biofuel production, erosion and flood regulation. The idea was to create indices to be able to compare these services among watersheds and evaluate best land management practices. Considering multiple ES at the same time we can develop a better understanding of the interactions and interdependencies in ecosystem components. Research using SWAT output variables that would be specific to one type of ES, could in fact be used to measure several ES. For example, among SWAT's output variables biomass could be interpreted as a biofuel ES variable, but along with soil carbon values, it could also be used to measure carbon sequestration. SWAT can be used to estimate the potential contributions by a particular land use and calculate changes in relation to climate change (Post et al., 2008). Moreover, changes in biomass in the landscapes, as during fallow or land retirement, could be measure using SWAT to estimate changes in water quality (Secchi et al., 2007).

The work by Fan and Shibata (2014) in Japan serves as an example of how SWAT can be applied to measure multiple provisioning ES and use that information for decision making that could lead toward sustainable development outcomes. The analysis by Fan and Shibata focused on understanding water yield fluctuations as a spatially and temporally dynamic provisioning ES for electricity production, residential use, and irrigation purposes. SWAT water yield outputs were analyzed seasonally and were used to conduct cost assessment evaluations. The economic value for electricity was calculated for each HRU and for each type of service provided. Using the unit price for electricity, water yield, and a conversion factor of electricity production, the services rendered seasonally by the watershed to the hydroelectric were estimated. Similarly, resident use and irrigation costs were estimated for each HRU. The water yield output data at the HRU's level was used to conduct a zonation analysis, which was later used to assign conservation priorities to areas with greater impact on water production and retention in the watershed.

4.2.2. Regulatory services

In addition to water yield provisioning as in the study by Fan and Shibata (2014) in the previous example, SWAT can also be used to measure regulatory ES. Soil erosion from the watershed and sediment deposition in reservoirs reduces the lifespan of hydroelectric power plants. SWAT can be used to estimate sediment deposition as a regulating ES. Furthermore, while costs due to sedimentation can be high for hydroelectric plants, there are other environmental and social costs involved that are not usually accounted for. Disruption to natural levels of sediment and nutrient flow can affect downstream habitats, human activities such as fishing, and increase the risk of floods among others. To address this problem one potential solution is investing in conservation practices and land use conversions that could contribute in trapping sediments in surface runoff (Arias et al., 2011). Through simulation and evaluation of land use scenarios in SWAT where different landscape components (forest, pastures, agricultural land, etc.) are configured in different arrangements, users and decision makers can more clearly support actions that would lead to greater environmental services while reducing negative externalities.

In addition to erosion control, SWAT can also simulate many other regulating ES. Carbon stock assessment is essential for analyzing the impact of land use conversion on climate change and vice versa. The work by Post et al. (2008) on soil carbon storage illustrates how modeling tools can be used to anticipate carbon stock changes. SWAT has also been suggested to understand flood regulation as an ecosystem service process by studying the hydrologic connectivity of the landscape (Golden et al., 2014; Liersch et al., 2013; Logsdon and Chaubey, 2013). Furthermore, SWAT has been used to measure evapotranspiration to maintain soil moisture condition as an ES to improve water conservation (Immerzeel et al., 2008). Yet, the most common regulating ecosystem service measured using SWAT is water quality. Sediment, nutrient, and pesticide output can be used to assess the impact of human activities on water resources (Lautenbach et al., 2013; Logsdon and Chaubey, 2013; Secchi et al., 2007; Bekele and Nicklow, 2005).

4.2.3. Supporting services

The direct use of SWAT for the analysis of supporting ES is less common. This may be because supporting services in general are not directly used by people. Hence, they need to be indirectly quantified, which is challenging as it may lead to double counting when valuating ecosystem services (Hein et al., 2006). Yet, supporting services are necessary for ecosystems to function properly. Examples of such services include soil formation, nutrient cycling, and photosynthesis/primary productivity. Outputs for these types of ES are more challenging to model, a limitation that also affects SWAT. Among the various supporting services, the services rendered by ecosystems to provide habitat to species could be included in this group. The degradation of the environment is associated with a reduction in the ecosystem's capacity to regenerate resources and host species and populations. Hence, failing supporting ES reduces the capacity of the environment to renew itself, which is essential for the continuation of other services. In this manner, biodiversity as a supporting service can be indirectly quantified in SWAT by measuring habitat change and/or habitat loss.

Changes to vegetative cover, climatic patterns, or the incorporation of infrastructure, have geomorphological and hydrological effects on ecosystems. Changes of this sort in the landscape have direct impacts and modify river and stream features such as flow, river bed, and bank stability. Consequently, habitat degradation can alter water and nutrient budgets in ecosystems and impair biological communities (Qiao et al., 2015). The research by Caro-Borrero et al. (2015) showcases the use of SWAT for evaluating stream conditions for macroinvertebrate and macrolgae diversity. The study combines geomorphological, hydrological, and biological features to examine stream functionality in the Magdalena-Eslava river sub-basin in Mexico. Given that the presence of organisms in a particular habitat is an expression of their evolutionary adaptation to the conditions in that environment, changes in water quality can be assumed to result in habitat degradation and in turn in biodiversity loss. An understanding of the biological communities associated with stream conditions is required to model the potential impact on biodiversity triggered by changes to the watershed. Extreme water flow events that follow changes to the environment could result in drastic increases or reductions in sediment and nutrient fluxes. SWAT can be used to estimate these changes, which in turn could be used to predict potential impact of habitat degradation as supporting ES.

Likewise, changes in the vegetative structure and composition of the landscape can also be assumed to affect supporting services in natural and/or agricultural ecosystems. In this sense, research using SWAT to compare the impact of different land use systems could be interpreted to indirectly evaluate changes in supporting services. Such would be the case of examining the impact of invasive species on the biophysical properties of the watershed. The work by Qiao et al. (2015) examined the effects of the introduction of eastern red cedar (*Juniperus virginiana*) on the hydrological properties of a predominantly grassland watersheds in Oklahoma. Compared to herbaceous vegetation, the deeper root systems of the woody perennials, along with their greater rainfall interception capacity, can lead to changes in soil moisture and water balance. Hence, changes in the structure and composition of the ecosystem is expected to affect its capacity to function properly. Qiao et al. (2015), as other studies looking at supporting services, used output variables in SWAT that would be considered more relevant to provisioning and/or regulatory services (such as water yield, biomass, sediment yield, etc.) to quantify supporting services. Given the nature of supporting services, changes in these would directly affect provisioning and regulatory services, and therefore by estimating the latter, inferences can be made on the former.

4.2.4. Cultural services

Cultural services involve an array of outdoor recreational activities such as hiking, camping, swimming, or aesthetic services such as mountain viewing, landscaping, and spiritual services such as ceremonial/sacred sites, belief systems, etc.; therefore, the application of hydrological models such as SWAT to evaluate cultural ES is less common (Milcu et al., 2013). It is not intuitive how a hydrological model such as SWAT could be used to provide cultural services information for management and policy making. In addition, the concepts used for cultural indicators can be sometimes vague in terms of definitions, purpose, and processes (Hernandez-Morcillo et al., 2013). In the case of evaluating cultural services, as in supporting services, SWAT can indirectly measure the quality of the environment that hosts the cultural service. As an example, this would be the case of assessing the capacity of the stream network to provide swimming opportunities.

For the purpose of comparing human perceived versus potential ecosystem services, a survey questionnaire and a SWAT project was developed by Baker et al. (2015). Instead of using SWAT to measure cultural ES, maps identifying the location of sites that provide the greatest amount of benefits were handmade by the community and built using the computer model. Hence, human perceived services were compared to SWAT provisioning ES. This socio-hydrological approach exemplifies alternative ways in which SWAT can be used as a tool that incorporates human dimensions into ES analysis. In the case of modeling cultural services, SWAT will require the inclusion of new variables to represent indicators that describe human perception and the demand for goods and services to be able to asses these type of ES (Plieninger et al., 2013).

4.3. SWAT modeling of ES to support decision making

SWAT modeling can be used for the management of natural resources and the development of payment for ES (PES) policies and implementation (van de Sand et al., 2014; Palao et al., 2013; Arias et al., 2011; Immerzeel et al., 2008). SWAT allows the user to estimate the impact of management actions prior to execution in order to contribute to an information-based decision making process (Quintero et al., 2009). Through the proper application of the model, data outputs can help decision makers evaluate the environmental pros and cons of management and land cover changes. Having a comprehensive understanding of the impact that decisions have over natural systems, from both a socio-economic and biophysical stand point, stakeholders can discuss the potential tradeoffs of management activities in order to identify sustainable solutions (Arias et al., 2011). From this stand point, information provided by SWAT modeling can influence conservation strategies beyond a particular watershed. SWAT modeling to support decision making processes has contributed to the development of national policies (Quintero et al., 2009), the identification of ES thresholds to be used as pollution indexes (Jayakrishnan et al., 2005), and the evaluation and diffusion of best management practices among others (Mwangi et al., 2015; van de Sand et al., 2014; Waidler et al., 2011).

SWAT has been used to simulate the incorporation of conservation practices at the upper basin in order to evaluate their impact at the lower basin (Welderufael et al., 2013). Such has been the case of the Ministry of the Environment in Peru. The International Center for Tropical Agriculture (CIAT), along with the international Fund for Agricultural Development (IFAD) and the Global Environment Facility (GEF), conducted hydrological and socio-economic analyses of the Cañete River Basin as a pilot study for the development of a new law related to payment for ES (Quintero et al., 2009). Cañete is one of the country's most important watersheds in terms of water supply for agricultural irrigation and domestic use. The research was intended to (1) determine the quantity of water yield produced by the watershed, (2) identify the sub-watersheds where conservation practices should be implemented to improve or maintain water balance conditions, and (3) estimate the economic value for sector-specific returns generated by the ES.

Peru's primary fresh water sources are Andean wetlands, which are fed by the glaciers and the precipitation in the high mountain region. Yet, with the threat of global warming and land cover change, a large percentage of the glaciers in the country have disappeared and water supply is expected to decrease in the coming years (Barnett et al., 2005). At the Cañete River Basin, five of the total 16 snow peaks melted between 1962 and 1999 (Cementos Lima S.A., 1999). Currently the Cañete River Basin is approximately 602,000 ha and covers 29 political districts in Peru. While the watershed's human population is not necessarily large (approximately 107,000 habitants compared to the 30 million in the country), the region is important in terms of agriculture, hydroelectric energy production, and tourism. Reductions in water supply would result in reductions in financial returns for these industries. Hence, multiple sectors have voluntarily agreed to collaborate with a government proposed scheme where payments are made for environmental services, and rendered (indirectly) to small landholders living in the upper basin for them to engage in land management practices that will help maintain the upper basin's capacity to provide ES to communities receiving the benefits of those services at the lower basin.

SWAT was used to identify the HRUs that provided the highest water yields per district in the watershed, as well as those that were the most vulnerable to changes in land cover. The results indicated that the upper and middle watershed contributed with about 77% of the stream flow (Uribe and Quintero, 2011). Given the amount of precipitation that these areas receive in addition to the accelerating snow melt processes of the glacials, presence of the watershed's natural habitat and erosion deterring agricultural practices will be important for the continuation of the basin's water-related ecosystem services. The results were relayed to the Ministry of the Environment in Peru, and in collaboration with different partners, these were used to describe concepts, formulate the premises, and identify the priority areas for the design of the PES scheme. Similar work has been conducted by CIAT in two departments of Colombia (Valle del Cauca and Antioquia departments) to target a Water Fund investment meant to conserve priority areas of the upper watershed that supplies water to the agricultural and hydropower industries located in the downstream areas (TNC, 2012).

Similarly, SWAT can be used in a more passive manner by showcasing unrecognized and undervalued ES. The study by Arias et al. (2011) estimates the impact of land use change on sedimentation for a hydroelectric power dam through forest conservation efforts, and proposes a framework for estimating PES as a mechanism to increase the dam's longevity (Arias et al., 2011). Other examples of SWAT for ES decision making processes include a binational study by Norman et al. (2012) to help solve socio-environmental justice issues under shared water management conditions. In this case, SWAT outputs were coupled with demographic metrics to convey information to land use planning managers. The use of SWAT proved to be effective at identifying hotspots of vulnerable communities when changes to the landscape resulted in the loss of ES. Like these examples demonstrate, the implementation of SWAT in policy formulation can help reach multi-stakeholder consensus in an unbiased and informative manner.

SWAT was not initially designed to model ES. Yet, given its capabilities its being adapted to enable this functionality (Vigestrol and Aukema, 2011). Given that many ES are spatially explicit, SWAT provides a landscape approach to modeling multiple factors that influence these processes. Vigerstol and Aukema (2011) provide a comparison between modeling tools for water-related ES and conclude that while models such as SWAT provide greater detail in their results leading to more accurate assessments, more general hydrological modeling tools such as the Variable Infiltration Capacity (VIC) and the Integrated Valuation of Ecosystem Service and Tradeoffs (InVEST) tend to be more accessible to users not as familiar with biophysical computer modeling (Vigestrol and Aukema, 2011), although they required processed data (e.g. evapotranspiration maps in the case of InVEST). Moreover, new tools are emerging such as the ARtificial Intelligence for Ecosystem Services (ARIES) model, which is meant to allow the user to customize the level of detail and expertise required for modeling ES. The premise is for a modeling tool like ARIES to potentially be functional to a wider range of users. However, ARIES is still in its developmental and documentation phase and validation of the model's capabilities is pending (Villa et al., 2014).

The models that are commonly used for assessing ES and the effects of human activities on natural resources are InVEST and MIMES (Gomez-Baggethum et al., 2014; Boumans et al., 2015). Both models use analytical frameworks that integrate natural and human components in a directional or bidirectional manner (Daily et al., 2009). Compared to SWAT, these models are focused on integrating natural capital (entities, structures and processes) with economic thinking and/or market value (Boumans et al., 2015; Tallis and Polasky, 2009). To achieve this integration, the analysis of relevant biophysical and socio-economic components and processes are estimated separately, and later coupled to allow interactions and feedbacks. Water related services such as water quantity and quality, erosion, agriculture and timber production are estimated in InVEST using the same fundamental hydrologic processes as in SWAT (Tallis and Polasky, 2009). Yet, InVEST includes additional modeling options to estimate pollination and cultural ES, as well as models used to derive the value of each ES analyzed (Tallis and Polasky, 2009). Compared to these models, SWAT is not currently capable of providing what has be considered a dynamic–integrated valuation approach to ES analysis (Boumans et al., 2015; Hein's et al., 2006). According to Hein's et al. (2006) four step conceptual framework for ES valuation, SWAT would be successful defining the boundary of the system being valued, comparing temporal and spatial scales, and evaluating biophysical components. However, it does not provide ES valuation through monetary references or indicators, aggregation or comparison of different types of values, or analysis of stakeholders. Unless further developed within SWAT as a one stop tool, socioeconomic analyses of ES need to be externally integrated to other analytical tools in a similar manner as MIMES and InVEST currently does (Cools et al., 2011).

As a traditional hydrological modeling tool, SWAT's data input and know-how requirements are sophisticated and not easily accessible to environmental managers and decision-makers (Vigerstol and Aukena, 2011). The fact that the model needs to be calibrated and validated using monitoring data to verify its effectiveness at forecasting is both a strength that attests to its predictive power, and a limitation when expertise, costs, and/or time resources are constrained. However, as an open source software tool, the model is well documented, and its worldwide application demonstrates its rapid approval and diffusion (Neitsch et al., 2011; Jayakrishnan et al., 2005). SWAT has become an ecosystem modeling technology broadly accepted in various fields of study such as hydrology, agriculture, ecology, and others (Krysanova and White, 2015). In addition, SWAT developers are moving forward toward making SWAT more user friendly to accommodate non-scientists. The development of programs such as QSWAT or SWAT-CUP are meant to provide access to potential users that do not have an ArcGIS license, and to facilitate the calibration/validation, sensitivity, and uncertainty issues that arise from modeling. Also, in terms of data analysis, VIZSWAT was developed to help interpret and visualize spatial data outputs in SWAT. In addition to these efforts, which intend to make SWAT more accessible and practical, the model's flexible data integration structure enables users to customize the tool with software updates, that include parameters particular to a site or produce additional outputs of interest (Notter et al., 2012).

It is clear that some ES are more easily quantifiable than others in SWAT. Provisioning and regulatory services are the primary areas in which the model can contribute to ES quantification. Given the nature of supporting and cultural services, their quantification may not be straight forward in SWAT or through other available models (Vigerstol and Aukema, 2011). The classification of ES may vary based on context and interpretation. Many of the output variables in SWAT can be used interchangeably to make diverse assessments of ecosystems and evaluate specific or multiple services. Guidelines have not yet been set for applying SWAT as an ES modeling option. At this point we can confirm that based on years of measured data and the inclusion of empirical models, SWAT is effective at estimating various provisioning services. Moreover, SWAT's process-based nutrient biogeochemical submodels can be used to measure many regulating services, and these capabilities are becoming more relevant to ES modeling as nutrient loading is expected to worsen in the coming decades (Radcliffe et al., 2015; MA, 2005).

The continued software development of SWAT could expand the types of ES that can be modeled and may include feedback mechanisms through the action of beneficiaries and service flows. This is what ES models such as ARIES are striving to achieve. ARIES is being developed to model the theoretical production of ES (sources), which is what SWAT can currently do, as well as the beneficiary's usage or demand for services (users), the actual transfer of services from production sites to users (flows), and the features (human driven or not) that deplete or alter the service flows (sinks) (Bagstad et al., 2014). By modeling these different ES feedback mechanisms, a more comprehensive understanding of ES dynamics can be conducted to differentiate between potential and actual consumption. To achieve this, in addition to using deterministic and process-based models as in SWAT, ARIES makes use of Bayesian networks to determine probabilistic relationships between the data inputs (Bagstad et al., 2014). This allows tradeoff between the different system components to be compared as quantitative or relative ratio values. However, if relative values are used, accuracy and applicability of modeling outputs may be reduced and limit their use to quick assessments and general inferences of ecosystems, which may or may not be sufficiently robust for decision and policy making. In the meantime, the continued application of SWAT in decision-making facilitates dialogue between SWAT experts and decision makers for informing water management, evaluating implications of SWAT results, and discussing the importance of generating basic information to enhance simulation accuracy.

5. Conclusions

Research interest and efforts to measure ES and the impact of human activities on these has been grown rapidly in the last decade. While the concept of ES involves a broad set of components and processes, along with the myriad of benefits humans obtain from them, recent attempts to classify and measure ES reflect our need to improve their management. Faced with the rapid changes in land cover, natural resources, and environmental health, which have led to an increased need for scientifically-sound policy making, tools such as SWAT are helping lead the way for understanding integrated ecosystem processes. By providing answers to natural resource management questions, SWAT is able to evaluate ES performance. Hence, beyond its original function as a hydrological model, SWAT can be used to study ecosystem processes in a systematic manner. While the model may be preferably used to simulate provisioning and regulating services, proxy variables can be used to estimate associated supporting and cultural services, although further data manipulation is required to transform models of ES potential to realized use. Further software development is required if the model is to become a conventional ecosystem modeling tool. In the meantime, a systematic guide could help assist users in utilizing SWAT's current modeling capabilities to estimate provisioning, regulating, supporting, and cultural services. The creative use of the model outputs is welcomed by its developers to continue discovering ways in which the model can be improved for evaluating the multiple ecosystem processes and services that exist in nature.

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