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Review

# A comparison of tools for modeling freshwater ecosystem services

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ABSTRACT

Interest in ecosystem services has grown tremendously among a wide range of sectors, including government agencies, NGO's and the business community. Ecosystem services entailing freshwater (e.g. flood control, the provision of hydropower, and water supply), as well as carbon storage and sequestration, have received the greatest attention in both scientific and on-the-ground applications. Given the newness of the field and the variety of tools for predicting water-based services, it is difficult to know which tools to use for different questions. There are two types of freshwater-related tools – traditional hydrologic tools and newer ecosystem services tools. Here we review two of the most prominent tools of each type and their possible applications. In particular, we compare the data requirements, ease of use, questions addressed, and interpretability of results among the models. We discuss the strengths, challenges and most appropriate applications of the different models. Traditional hydrological tools provide more detail whereas ecosystem services tools tend to be more accessible to non-experts and can provide a good general picture of these ecosystem services. We also suggest gaps in the modeling toolbox that would provide the greatest advances by improving existing tools.

## 1. Introduction

Interest in measuring ecosystem services – the benefits nature provides to people – has increased dramatically in recent years (Daily, 1997; MA, 2005; Anonymous, 2009). Ecosystem services have been identified by members of many sectors, including government agencies, the business community, and NGO's, as an important piece of land planning, management, environmental markets, citing, and mitigation (MA, 2005; Chambers et al., 2005; Goldman et al., 2008; Waage et al., 2010). Approaches to measuring ecosystem services show great promise for explicitly linking conservation with human well being and conservation organizations increasingly invoke the needs of people as a rationale for conservation (Tallis et al., 2008). As the importance of ecosystem services is recognized, there has been a growing need for tools and models that can provide information to decision makers on service provision and the effects of land use management on those services.

Several research teams have begun developing tools to quantify and visualize water-related ecosystem services, arguing that if these services could be quantified, or at least visualized, stakeholders and leaders would be more likely to use this information as part of the decision-making process that would ultimately yield more sustainable choices. At the same time a number of traditional hydrological models that assess the drivers of ecosystem services can be adapted for many of the same applications. With the availability of new tools, it can be difficult for decision makers to identify which tools are appropriate for their applications and when modeling is even necessary. It is important to consider what a model was designed for and how well it fits intended applications. Other factors to consider include the spatial and temporal scale of analysis, the computational intensity, the data availability and data needs of the models, the underlying modeling equations and the level of testing and validation the model has undergone.

Water is a core component of both human well-being and a thriving economy. Therefore we focus on tools that quantify water-related services or ecosystem processes and the hydrologic attributes that drive them (Box 1). Water flow regulation ensures sufficient water supply, controls against floods, and provides instream flows for fish; water quality regulation provides clean water for humans and species on which humans rely; and sediment regulation can minimize costs of removing sediment from downstream water resource structures. Although clearly all components of an ecosystem and all ecosystem services are interdependent, freshwater services and attributes are frequently modeled

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### Box1. Water related ecosystem services

Many regulating, provisioning, supporting, and cultural services are related to water. Some of the services that people benefit from most directly include the provision of drinking water, irrigation water, hydropower, fish, opportunities for recreation, and flood mitigation. Underlying these services are the more basic hydrologic attributes of quantity, quality, location, and timing that are driven by ecosystem processes (Brauman et al., 2007). Water retention, water yield, natural water filtration and sediment regulation are important components of the attributes and processes that produce these services and may be considered supporting services themselves.

**Water retention** is a key component of water quantity. It is an important piece of the hydrologic cycle, acting as a distributed reservoir of water that is released over time. Retention provides a buffer for both water supply shortages and flooding. Water retained by the landscape in the upper basin allows water supply to extend further into the dry season, when water is more valuable. Water retention during a storm flattens the flood peak, which can reduce flood damage. Holding water on the landscape also aids in replenishing groundwater, the source of baseflow for many streams.

**Water yield** is another important component of water quantity, contributing to water availability for consumptive use (e.g. drinking or irrigation) or in situ water supply (e.g. water for hydropower or fisheries). Management decisions can alter the distribution of water in the hydrologic cycle through land use change. Therefore, if the landscape yields more water due to a land use change, another component of the hydrologic cycle, such as groundwater, may be losing water. The seasonal timing of runoff patterns for individual storms is a critically important component of water yield. Water yield in conjunction with water retention is important for understanding patterns and timing of flooding events.

**Natural water filtration** is a key ecosystem process underlying water quality and is critical for both consumptive water use and instream water quality that affects fisheries and recreation, among other services. As water flows off the landscape, it may pick up a variety of pollutants such as nutrients from agricultural fertilization or residue from motor vehicles. Without natural filtration, these pollutants enter streams and lakes, altering the quality of the aquatic habitat and degrading the quality of water for downstream users. Vegetation along the flowpath, however, can provide a natural filter for those pollutants before the overland flow reaches a water body.

**Sediment regulation** is another important process contributing to water quality. Sediment movement from the landscape and throughout the river channel is an important process that is part of the natural evolution of a river basin. Increased erosion due to clearing of land or other management actions, however, can cause an excess sediment load to the system. Increased sediment can shorten the life of water management structures and decrease the operational capacity of hydropower, water supply, and flood control reservoirs. Increased erosion can also impair water quality, causing increased turbidity and degrading aquatic habitats, affecting fisheries and recreation.

separately and are more tractable than some less tangible ecosystem services such as esthetic or cultural values. As a note, although “green water” (essentially water vapor), is an important component of the hydrologic cycle (Jewitt, 2006) and is beginning to be recognized for its role in ecosystem services (Maes et al., 2009), green water isn’t currently well incorporated in the models we are reviewing. For this comparison we focus on tools that are appropriate for the river basin scale as this is most useful for integrated water resource management. A river basin is defined by boundaries within which management actions can affect the flows and quality of water in the river to which all water that falls within the boundary eventually runs.

Based on literature and interviews with the developers of some of the featured tools, here we review several examples of both ecosystem services specific and traditional hydrological models and their utility to practitioners. All the models we consider are free, publically available, and actively supported. We limited the review of models to two from each category, traditional hydrologic tools and specific ecosystem services tools, to allow a more detailed comparison than would be possible if all available tools were included. SWAT and VIC were selected based on their variety of application and their focus on modeling similar attributes to the more specific ecosystem services models. InVEST and ARIES are fairly well developed among ecosystem service specific tools and are the ecosystem services tools with the most applications from which to draw experiences. We offer guidance on selecting tools for particular applications, with the goal of helping practitioners become more effective in their work. As these tools are still in development, this type of review and guidance has not previously been available and will make water-related ecosystem service modeling more accessible to practitioners working in systems around the world.

## 2. Summary of tools

Here we review examples of two different classes of tools: traditional hydrological tools and ecosystem services tools. SWAT and VIC are examples of traditional hydrological tools that focus on ecosystem services drivers and require post processing for ecosystem services assessments. InVEST and ARIES represent a new breed of ecosystem services specific tools, focusing mainly on end services and visualization of these services across a landscape. There are several areas of similarities between these models, especially between tools within the same category.

### *2.1. SWAT (soil and water assessment tool)*

SWAT (Arnold et al., 1998; Arnold and Fohrer, 2005) was developed for the USDA’s Agricultural Research Service (ARS) to evaluate the impact of land use changes on watershed yield, sediment, and agricultural pollutants in a river basin. SWAT models several different hydrologic attributes that underlie water-related ecosystem services. The tool models the volume and quality of water on a daily basis, which can be used for assessments of ecosystem services such as freshwater for municipal, industrial and agricultural uses, instream flows that support fisheries and recreation, flood risk, and inflows for hydropower and other water resource infrastructure (Neitsch et al., 2004, 2005). SWAT is a continuous daily model that is intended for study of long-term trends such as the buildup of pollutants over time, and not for one-time events such as flooding from a single storm. SWAT accepts a range of input data, but the specific requirements for each user depend on which module(s) they need to run for their specific analysis.

SWAT models snowpack and snowmelt, infiltration and soil routing of water, movement into and out of the shallow aquifer system, evapotranspiration, and water diversions. It uses a simple plant growth model to simulate the change in land cover over time and provides estimates of removal of water and nutrients from the root zone, transpiration and biomass production. SWAT can model both the migration and chemical transformation of nitrogen and phosphorus in the watershed and can also model pesticide movement through the watershed. The pesticide models accommodate multiple pathways including surface runoff and percolation into soil layers. As flows are routed downstream, the tool can account for reservoirs and diversions in the main channel. Users can specify land management practices such as growing season length, fertilizer application, and irrigation to view alternative scenarios.

The available outputs from SWAT are extensive. The model provides results by subbasin at each time step as well as summarized data for combined time steps (into a month or a year) and the values at the end of the modeled time period. The outputs describe water movement at all locations in the water cycle, from evapotranspiration to subsurface flow to volume of water applied for irrigation. The model also provides detailed output data on the movement of nutrients and pesticides through the watershed, if the user has chosen to model these processes.

#### 2.1.1. Applications

SWAT has been applied widely in the U.S. and around the world, with hundreds of published examples. Applications include the assessment of hydrologic and pollutant impacts due to water use and land management (Prochnow et al., 2008; Schilling et al., 2008). It has also been used to analyze pollutant sources and actions needed to meet Total Maximum Daily Load (TMDL) (Schilling and Wolter, 2009), quantify climate change impacts (Stone et al., 2001), estimate soil erosion (Shen et al., 2009), assess hydropower potential (Kusre et al., 2010) and evaluate best management practices (Gassman et al., 2007). Although versatile, running the various modules of the model requires detailed data inputs which the user may not have available. The model user should also allocate time for learning the model if she has not had previous experience with SWAT. Expertise in hydrology is highly recommended for learning and using SWAT, limiting the number of potential users.

### 2.2. VIC (variable infiltration capacity) model

The VIC (variable infiltration capacity) 4.1.1 model (Liang et al., 1994, 1996; Nijssen et al., 1997) is a large-scale gridded hydrologic model that is most appropriate for large river basins where water yield and stream flow are the main variables of interest. It is also useful if the assessment includes aspects of climate change impacts, such as possible change to streamflows. Grid cells are 1 km or more across, and land surface interactions are modeled separately for each cell. Model time steps vary from hourly to daily, depending on available input data and objective of the modeling exercise. Required input data include meteorological data, elevation, land cover and soil characteristics.

The model estimates water movement between the atmosphere, ground surface, soil layers and subsurface by precipitation, evapotranspiration, infiltration and runoff. VIC includes a more complex accounting of water movement through different soil layers than the ecosystem services specific models. The model can account for adjustments in water movement from soil freezing or melting ground ice, and it accounts for in-ground snow pack, vegetation canopy snow and snow on top of frozen lakes. A routing model, which must be downloaded separately, then takes yield from individual cells and routes it to the main channel and through the channel to the outlet.

VIC calculates dozens of output variables for each time step, which break down each piece of the water and energy budget for each pixel, and the user can preselect which variables to include in the output file. There are several scripts available for post processing of the VIC output, such as aggregating time steps (for reducing the size of the output file), routing water flows in streams, and plotting results.

#### 2.2.1. Applications

The VIC model has been applied to a variety of large scale hydrological investigations, dozens of which can be found in published works. The model has been used to estimate the water balance of large river basins (Abdulla et al., 1996), for simulating stream flow in continental-scale basins (Nijssen et al., 1997), for stream flow forecasting based on changes in El Nino – Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) (Leung et al., 1999; Hamlet and Lettenmaier, 1999), to assess the impacts of land use change on streamflows (Mattheussen et al., 2000), for a global assessment of streamflows (Nijssen et al., 2001), and most notably for evaluating the expected impacts of climate change on water supply (Hamlet and Lettenmaier, 2000; Elsner et al., 2010). Several methods have been developed for processing outputs from climate change models to create inputs that feed into the VIC model (Maurer, 2007, 2009). Scripts developed by VIC users, and available for download, allow users to make batch runs of VIC to evaluate a range of scenarios. Like SWAT, VIC models hydrologic attributes of ecosystem services that can easily be translated into ecosystem services. VIC is less useful for comparing across several services, including sediment loads, pollutants and non-water services, which an ecosystem service specific model or SWAT, may cover. The model is intended for large scale analysis and therefore is not appropriate for study areas smaller than a river basin. VIC requires a large computing capacity and hydrological expertise, either of which may rule this model out for some users.

### 2.3. InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs)

The aim of the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) tool is to model and map a suite of ecosystem services across the landscape to elucidate general patterns and changes in ecosystem services caused by land cover changes (e.g. due to policy, management or population growth) or climate change impacts. InVEST has both simple (Tier 1) and more complex (Tier 2) models (Tallis and Polasky, 2009). Only the Tier 1 models are currently freely available in a software package, so we focus on reviewing these. Each service is modeled separately, so that stacking of services takes place with the combination of model results. The current version of InVEST runs on an annual basis and is intended for a relatively quick assessment of services across the landscape. In the U.S. a typical spatial scale would be modeling at a 30 m cell size, while in other locations where detailed data are less accessible, the model may operate on one to 10 km cell sizes. The data inputs required for each model vary depending on the service, with data formats in GIS raster grids, GIS shapefiles or database tables.

The InVEST 2.1 tool can model reservoir hydropower production, avoided reservoir sedimentation, and water purification, as well as a number of marine and non-water related ecosystem services. Future versions of the tool are expected to include irrigation and additional non-water services. InVEST hydrological models are based on simplifications of well-known hydrological relationships, such as the Universal Soil Loss Equation which is part of the Avoided Reservoir Sedimentation model, and calculations are performed on an average annual basis. Each InVEST model breaks the landscape up into pixels, whose size is based on the scale of the input data, and performs calculations on a pixel basis. Then, depending on the service being modeled, the model may combine results from groups of pixels in subsequent modeling steps.

The outputs of InVEST are GIS maps of intermediate modeling steps, final biophysical service levels and economic estimates (if the optional valuation step is run) for each pixel across the landscape. For example, in the Avoided Reservoir Sedimentation Model available outputs include the potential average annual erosion, the actual average annual erosion, the total sediment arriving at a downstream point of interest (such as a dam), the ability of each pixel to reduce erosion and an estimate of avoided dredge costs provided by reduced erosion.

#### *2.3.1. Applications*

InVEST can be useful to a wide variety of users, including local to international conservation organizations, government agencies and businesses: anyone with an interest in environmental management, assessing the trade-offs between ecosystem services, and examining changes in ecosystem service provision under different land use scenarios. The InVEST tool has been applied in a variety of locations around the world, including Hawaii, Oregon, and Colombia (Daily et al., 2009; Tallis and Polasky, 2009). Most applications have been run at a large river basin scale. The goal of the modeling exercises varies among sites, from conservation prioritization to comparison of future land use scenarios under different policies (Nelson et al., 2009; Daily et al., 2009). For example, in Hawaii, the InVEST tool is being used by a large landowner, Kamehameha Schools, to decide how to manage their lands to maximize ecosystem services and revenue (Daily et al., 2009, H. Tallis pers. comm.).

The ideal application for InVEST is to assess the impacts of land cover changes (due to policy or population changes) on multiple ecosystem services over a relatively large basin using a scenario comparison. The main limitations of the InVEST hydrologic models are their inability to account for seasonal or sub-seasonal variability, groundwater and water resource infrastructure that redistributes water flow. Users must also be aware of the simplification of hydrological processes inherent in the tool and the uncertainty this may represent. Several of these limits are expected be addressed by the subsequent releases of the model, which are currently under development. Finally, users of the InVEST tool would benefit from expertise in GIS as it can greatly reduce time required to run the models.

### *2.4. ARIES (Artificial Intelligence for Ecosystem Services)*

ARIES (Villa et al., 2009) is a web-based tool that allows users to evaluate trade-offs between ecosystem services, and to identify hidden stakeholders who may benefit from services within the area of interest. The user inputs as much local data as possible and the tool uses probabilistic Bayesian networks to uncover relationships between input data and ecosystem service values. This is in contrast to the other tools we are presenting here that rely solely on accepted biophysical relationships to model the physical processes in the watershed. The ARIES tool defaults to probabilistic relationships based on data stored from other similar sites around the world, but in cases where sufficient local data are available the tool can employ biophysical relationships. The artificial intelligence driver of the tool works to improve upon the functional relationships to decrease the level of uncertainty. A typical spatial scale in the U.S. would be modeling at a 30 m cell size, while in other locations where detailed data are less accessible, the model may operate on larger cell sizes.

The user can apply ARIES at varying levels of detail, depending on the local input data available and the objective of the application. At its most basic level, the user can take advantage of data stored within the tool to do a rapid assessment with a large range of uncertainties; at its most complex level, ARIES can be applied as a custom built model using detailed data and local knowledge to build relationships between input data and service outputs that account for social, economic and ecological peculiarities of the study site and produces results with lower uncertainties. A preliminary version of ARIES is available online. With this and subsequent releases, the tool will cover the following services: flood control, sediment regulation, subsistence fisheries, salmon yield, nutrient filtration, water supply, and several non-water related services.

The result is a portfolio of ecosystem assets for the area, an assessment of their realized and potential value, and a description of the relationships between the ecological and economic data inputs and the results. The user also has the option to download the output into GIS data files that she can use as needed in her own GIS software. The format or units of the results depends on the service being modeled. Mapped results may be given in relative values or in appropriate biophysical values, such as tons of sediment. For services that can be modeled biophysically, the timeframe that is captured by the final results also depends on the service, ranging from a specific storm event to an annual sum. The outputs of the tool are provided as a range that indicates the sensitivity of the output variables to the input data. The map outputs of the tool display where ecosystem services are provided and where people benefit from those services, as well as the flow paths between the source regions and use regions.

#### *2.4.1. Applications*

ARIES may be useful to a wide variety of users, including local to international conservation organizations, government agencies and businesses. It is likely to be useful for anyone interested in environmental management and visualizing ecosystem service dynamics, assessing the trade-offs between ecosystem services and assessing where they are provided and used and the flow characteristics of ecosystem services between provisioning and use. Current applications of ARIES by the development team are in Madagascar, Puget Sound, USA and Vera Cruz, Mexico (K Bagstad pers. comm.). These applications are intended for testing the tool as well as answering on the ground policy questions. For example, in Madagascar the team is working with Conservation International, local non-governmental organizations, and local government agencies to investigate sedimentation as well as biodiversity and carbon sequestration and storage. In Puget Sound the team has run the tool for sedimentation, flood control, carbon, views and open space services to better inform local government agencies on planning and possible flood control actions.

One example of an ideal application of ARIES is for land use planning, to help determine where preservation or restoration of a natural land use is most critical to maintain a set of natural services. Locations of interest in this case may be areas where multiple ecosystem services are provided or an area of critical service flow that acts as a choke point for the flow of services to beneficiaries. A limit of ARIES is the lack of transparency of the model code due to its complexity. This may hinder the communication of model relationships and results to decision makers and reduce its acceptance. While users can change key model parameters in the Java and Clojure code, the Artificial Intelligence framework is not intuitive to many users and the complexity of the code may limit the accessibility.

## 3. Choosing among tools

Before embarking on the tool selection process, practitioners should assess whether an ecosystem services assessment is the appropriate approach for their work. There are guides and tools available to walk practitioners through this assessment process, such as the World Resources Institute *Guide for Decision Makers* (Ranganathan et al., 2008) and a screening tool developed by the World Wildlife Fund, The Nature Conservancy and the Natural Capital Project (McKenzie et al., 2008). If an initial screening process indicates that ecosystem services is indeed a suitable approach, the next step is to determine whether modeling is necessary for the questions at hand. It may be possible to do an overview assessment of ecosystem services, such as simply indicating which services may be affected by policy changes in the area of interest, or perhaps a model has already been created and run for the area and could be adapted for the ecosystem services assessment. Modeling requires dedicated time and financial resources, and the practitioner should be sure that the modeling effort is worth the investment.

Once a user has decided that a more detailed ecosystem services assessment is called for, she should carefully consider the specific questions she is trying to answer, what services she is interested in, and the scale of the study. The choice of tool should take into account the level of detail required by the question at hand. For example, a coarse scale tool such as VIC is not appropriate to answer site-level questions and a site-level tool is not broad enough to address watershed wide issues. The user must evaluate what types of data are available or can be collected for the area of interest within the timeframe and budget of the project.

The type of expertise available for the project, particularly GIS and hydrological expertise, are critical in identifying appropriate models to use (Table 1). Other considerations include the desired outputs of the models, whether different scenarios are being compared, how important temporal variability is for the questions being asked, if multiple services are being examined, and if so, whether they are going to be stacked (Table 2). Furthermore, in order for the modeling exercises to be most useful for on the ground policy applications, users need to consider how particular modeling approaches are likely to be received by the stakeholders. For example, some stakeholders may be most comfortable with models that they know have been extensively peer reviewed, whereas other groups may be eager to use the latest, most innovative modeling techniques.

### 3.1. Broad recommendations for best applications

If users are interested in comparing multiple ecosystem services simultaneously or in looking at both water related and non-water related ecosystem services, then an ecosystem services specific tool (InVEST or ARIES) is the most appropriate (Fig. 1). Additionally, if users are interested in a quick examination of specific hydrological services requiring minimal data, then these simplified ecosystem services specific tools are also appropriate. On the other hand, if users are interested in specific hydrological services and they have appropriate data (e.g. daily or weekly as opposed to just annual values) and the expertise (hydrologist) needed to run the models, we recommend using one of the hydrological models (SWAT or VIC). Additionally, if extensive peer review or scientific consensus of the underlying processes is needed, these models should be used even though they are more data intensive.

**Table 2**
Basic inputs and outputs for water-related ecosystem services tools.

| | SWAT | VIC | InVEST | ARIES |
|---|---|---|---|---|
| Key data inputs | | | | |
| Precipitation | Daily | Hourly | Ave annual | Best avail |
| Topography | Yes | Yes | Yes | Yes |
| Soil type | Multi layer | Multi layer | Single layer | Single layer |
| Snow water equivalent | Yes | Yes | No | No |
| Key outputs | | | | |
| Water yield | Daily | Hourly | Annually | No[a] |
| Evapotranspiration | Daily | Hourly | Annually | No[a] |
| Flows | Daily | w/routing model | No | Yes |
| Sediment retained | Yes | No | Yes | No[a] |
| Nutrients retained | Yes | No | Yes | No[a] |

[a] ARIES does not explicity provide the user with these specific outputs, but rather wraps them up into reporting on results such as an economic valuation or ecosystem profile.

The user needs to consider a variety of additional factors in choosing between ecosystem service specific models. AIRES requires much less data and expertise than InVEST, and once verified, we would recommend AIRES for policy makers and other non-technical users, or in situations with very limited data. InVEST has the advantage of a relatively transparent code that can be easily described and altered if needed. It uses biophysical relationships that, despite their limits and assumptions, are widely accepted by scientists as good estimates of physical reality. In addition, when they are completed, the InVEST Tier 2 models will allow existing hydrological models, such as SWAT or VIC, to be brought into a common platform. For a user-friendly interface requiring minimal data inputs we recommend the ARIES model. This tool also allows the user to identify beneficiaries and flows of services. Because the ARIES model uses machine learning to identify the relationships among variables, it may not be appropriate where peer reviewed scientific consensus of the underlying processes are important. In choosing between hydrological models, we recommend SWAT if the user has detailed data and is interested in sediment and pollutants in addition to water yield. If the user is only interested in water supply and is working on a larger scale, we recommend VIC. In addition VIC has been used more extensively for regional climate change studies.

**Table 1**
Summary of freshwater ecosystem services tools.

| Model | Freshwater services | Time step | Scale | Platform |
|---|---|---|---|---|
| InVEST[a] | Nutrient filtration, hydropower, irrigation, avoided reservoir sedimentation, storm peak mitigation | Annual | 30 m–10 km grid cells | GIS |
| ARIES[b] | Flood control, sedimentation, nutrient filtration, water supply | Monthly to annual | 30 m–10 km grid cells | Web-based |
| SWAT[c] | Water yield, sedimentation, water quality | Daily | Subbasin | Windows or GIS |
| VIC[d] | Water yield | Hourly to daily | 1–50 km grid cells | LINUX/UNIX |

[a] Developed and maintained by the Natural Capital Project, a collaboration of World Wildlife Fund, The Nature Conservancy, and Stanford University: www.naturalcapital.org.

[b] Developed and maintained by the University of Vermont Gund Institute for Ecological Economics and in collaboration with Earth Economics and Conservation International: http://www.ariesonline.org/.

[c] Developed and maintained by the US Department of Agriculture's Agricultural Research Service (ARS): http://swatmodel.tamu.edu.

[d] Developed and maintained by a group at the University of Washington's Department of Civil and Environmental Engineering, lead by Dennis P. Lettenmaier: http://www.hydro.washington.edu/Lettenmaier/models/vic.

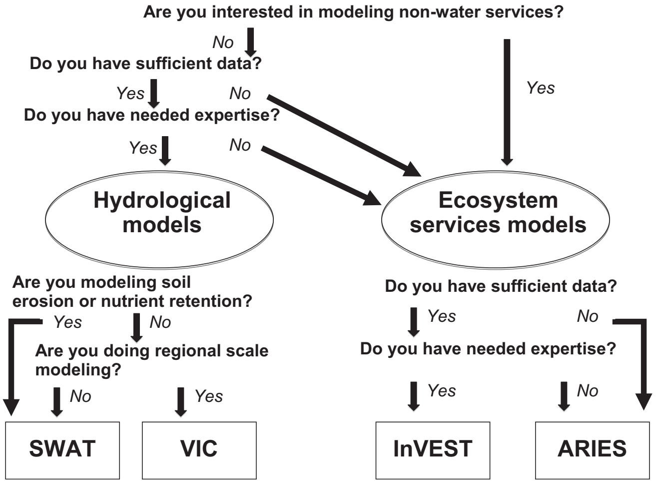

**Fig. 1.** Schematic of decision points and questions to ask in choosing a model.

## 4. Conclusions

In conclusion, this is an exciting time for the field of ecosystem services with new innovations emerging regularly. There are a number of tools that are well developed or in the process of being developed that can help us to visualize and quantify ecosystem service benefits on the landscape, but it can be difficult to choose which tool is most applicable. Here we have provided broad recommendations for selecting tools to make water-related ecosystem service modeling more accessible to practitioners working in systems around the world. As these tools continue to develop and be applied under different conditions, the experience base of ecosystem services assessments will grow and feed the refinement of guidelines for appropriate applications of the tools.

There is no one best model or tool; each has advantages and disadvantages. In many cases, more than one model is appropriate for the application. In particular, the two multi-service models that we compared accomplish similar goals but are based on different fundamental philosophies. The InVEST models are deterministic and are based on simplifications of widely accepted hydrological relationships. They have the advantage of clarity, with relatively simple code that users can understand and adjust when needed. Although ARIES is also open source, it uses probabilistic models based on spatial Bayesian networks in which users define relationships among variables. Where users are relying on predefined relationships and available data, the workings of the ARIES model can appear opaque. Its modeling code is much more complicated than InVEST and requires greater expertise or investment of time to adjust. However, ARIES does offer an opportunity to refine established biophysical equations for each specific location. For example, the Universal Soil Loss Equation was developed based on experiments in an area of particular landscape characteristics and may not provide as accurate results in some locations as others. InVEST allows users to choose between two versions of this equation, the original and a second for steeper locations. For areas where one of the two USLE equations is a good approximation or well accepted by stakeholders, InVEST may be the appropriate model to use. In contrast, ARIES allows the USLE equation to be modified, using the integrated artificial intelligence code, based on the local conditions and taking into account the full range of influencing factors.

The specific hydrological models we reviewed here offer peer-reviewed tools that have developed in complexity over time. They have been tried and tested on a variety of applications and incorporate the knowledge and experience of water resource professionals. They are calculated on a daily or weekly basis and capture seasonal or sub-seasonal variability, and one or both of them incorporate groundwater, snow, and infrastructural water diversions. However, these tools require specific expertise to gather the input data, run the models and interpret the results in a way that provides useful information on ecosystem services.

In addition to the models we review, there are many other ecosystem services tools that are valuable at smaller and larger scales, focus on non-water services, or are specific to a particular location. These include the Wildlife Habitat Benefits Estimation Toolkit (Kroeger et al., 2008), the Parametrix's EcoMetrix tool (Venner et al., 2009), World Resources Institute's many guidance documents and tools (http://www.wri.org/project/mainstreaming-ecosystem-services), the MEASURES Ecosystem Services Credit Calculator (http://www.cws.bse.vt.edu/index.php/research/project/ecosystem_services_calculator), and tools in development at the Environmental Protection Agency. There are also a number of water resources models that we were not able to include here but which could be used in an ecosystem services assessment, depending on the questions being addressed. These include FIESTA for hydrologic modeling in locations where fog capture is a major component of the hydrologic cycle (Mulligan and Burke, 2005), HEC-RAS for flood control (Brunner, 2001), the Water Evaluation and Planning (WEAP) system for modeling water services in the context of water resource infrastructure (Yates et al., 2005), and BASINS(Better Assessment Science Integrating point and Non-point sources, http://water.epa.gov/scitech/datait/models/basins/) which was developed by the EPA for a variety of water services and includes the nonpoint source model Hydrological Simulation Program Fortran (HSPF) for modeling water supply, sediment regulation and pollutant regulation (Bicknell et al., 1997; Lahlou et al., 1998). BASINS now interfaces with SWAT (Di Luzio et al., 2002).

One major gap in our understanding of these tools and their best applications is that there have been no formal quantitative comparisons of the different models using a common problem and input data. Currently some comparisons are underway between InVEST and SWAT and between ARIES and InVEST, but no results have been published. Such comparisons will be critical to evaluating the best uses for each of the models and to refining and improving them. Ecosystem services mapping and modeling is at the stage of "many flowers blooming" and it is now time to start comparing and assessing performance in a wide variety of settings. The potential for these models to propel decision makers toward more sustainable policies is tremendous. So that users and policy makers are not confused by competing models, now is the time for model performance comparison.

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