Approaches for Modeling and Monitoring Water Quality Outcomes for Agricultural Fields

Prepared for
Field to Market

August 15, 2017

LimnoTech

Water | Scientists
Environment | Engineers

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List of Abbreviations

AnnAGNPS	Annualized Agricultural Non-Point Source
APEX	Agricultural Policy/Environmental eXtender Model
ARS	Agricultural Research Service
BMP	Best Management Practice
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems
DWM	Drainage Water Management
EPIC	Environmental Policy Integrated Climate
FHANTM	Field Hydrologic and Nutrient Transport Model
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems
HSPF	Hydrological Simulation Program – FORTRAN
MANAGE	Measured Annual Nutrient loads from Agricultural Environments
NOAA	National Oceanic and Atmospheric Administration
NTrT	Nutrient Tracking Tool
RSET	Resources Stewardship Evaluation Tool
RUSLE2	Revised Universal Soil Loss Equation (2)
RZWQM2	Root Zone Water Quality Model (2)
SSURGO	Soil Survey Geographic Database
SWAT	The Soil and Water Assessment Tool
STEP	Stewardship Tool for Environmental Performance
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WQI	Water Quality Index for Agricultural Runoff

EXECUTIVE SUMMARY

Water quality models are mathematical tools that synthesize research and monitoring information to describe our best understanding of the complex relationship between land use and water quality outcomes. Models applied at the field scale simulate conditions for a particular area of cropland and include representation of the specific management conditions that occur on that land. This paper explores the status of these models and the monitoring programs that support model development and application, and it also identifies the investments needed to achieve an accurate, quantitative field scale model of water quality outcomes from implementation of conservation practices throughout the U.S.

Existing field and watershed scale modeling frameworks were compared to the characteristics of an "ideal" water quality model that provides the capability to accurately represent landside properties and best management practices. All of the models fell short of the idealized field scale model. Technical gaps relate to model configuration, computational limitations, and limits imposed by the structure of the model code. Watershed models, while useful when applied at the field scale, simulate conditions over a broad area of interest and it is often not feasible or practical to represent individual fields explicitly.

Some technical gaps related to model capabilities are the result of both the technical challenge of representing the process in the model, and the limited research with which to develop the equations. As an important example, coding a detailed representation of the processes required to simulate edge-of-field best management practices (BMPs) is currently a challenge. Emerging research will provide valuable information, but there is a lag in the time between a practice's popularization within the producer community and the availability of research data to parameterize its behavior.

Model predictions are inherently uncertain. It is not practical to calibrate models to the precise physical and management conditions for every field in a large geographic area because site-specific data are not typically available and the resources to conduct a modeling effort are usually limited. Therefore, when considering the overall skill of a model, it is important to evaluate whether the model is capable of reproducing observed flow and loading data without requiring site-specific calibration, based on appropriate regional input parameters and local slope and soils information. It is also important to communicate the uncertainty in model results, particularly as models serve as educational tools. Index models, which rely on a relative ranking of water quality conditions, have an advantage over process-based models in this regard because they do not require calibration and they are generally easier to understand and interpret.

Models integrate existing data in a structured manner consistent with our best understanding of environmental processes. As such, models are only as good as the data upon which they are based. Data required to test and verify model performance should ideally be available at frequent intervals to capture important time dynamics, and at both the field and watershed scale. However, water quality monitoring is still a moderately complex and expensive endeavor. Limitations in existing monitoring programs are related to coverage of crop type, geographic distribution, and spatial and temporal scale, as well as outcomes associated with specific BMPs for specific crops. Standardization in reporting monitoring results across all programs would help modelers more efficiently use results of monitoring studies.

The recommendations provided in this paper can eventually lead to the model skill and data availability necessary to develop a field scale water quality metric based on a process-based model. While achieving that aim at a national scale is not yet possible, much can be accomplished in the interim both by use of the index models as well as strategic use of process-based models where sufficient data and information exist.

WATER QUALITY APPROACHES AT THE FIELD SCALE

Background

A large number of modeling frameworks and tools have been developed over the past several decades to evaluate agricultural landscape processes, including the movement of water over and through soil (i.e., hydrology) and the associated movement and fate of sediment, nutrients, and pesticides. These tools were typically developed for research by government agencies or academic groups to investigate a particular set of research needs. Subject to a variety of factors, a subset of these research models underwent continued development and expansion, and were eventually made available for broader use to evaluate conditions on the landscape.

Models of interest for agricultural modeling can be broadly categorized as either field scale or watershed scale. While field scale models are recognized as being more accurate due to their greater detail, watershed models are included in this evaluation for two reasons: 1) only a limited number of suitable field scale models are available; and 2) some watershed models have the potential to provide sufficient detail to represent agricultural processes at the field scale.

Field scale models are tools that have been developed for the express purpose of simulating conditions for a specific area of land, including representation of the specific management conditions that occur within that area. In some but not all cases, field scale models also explicitly represent the variations in topography (elevation and slope) that occur in the area of interest. Watershed models, on the other hand, simulate conditions over a broader area of interest, often including both landscape and instream conditions. Due to resource constraints, it is often not feasible or practical to represent individual fields explicitly in a full watershed model. For example, representing individual fields in a 5,000 square mile basin would require the simulation of many thousands of land response units. Therefore, the most typical approach for a full watershed model application is to represent an average “lumped” condition representing land areas throughout the watershed or subbasin that have common land use/cover, soil, slope, and meteorological conditions.

Existing watershed models represent a wide range of capabilities with respect to simulation of specific agricultural management conditions. For example, the HSPF watershed model provides a generalized and highly customizable framework, but it’s use of “lumped” areas does not provide a way to explicitly represent the effects of planting, tilling, fertilizing, etc. on an individual field. On the other hand, agriculturally-focused watershed models such as SWAT and AnnAGNPS provide detailed options for representing cropland management conditions at the field scale. A significant limitation of these models with respect to field scale application is their inability to represent the routing of water and pollutants *within* the field.

The remainder of this section provides an evaluation of existing watershed and field scale water quality modeling approaches that address the following questions:

- What are the characteristics of an ideal water quality model for application to agricultural fields?
- What are the relevant existing water quality modeling frameworks, and how do those approaches compare against the ideal water quality modeling approach?

Characteristics of the Ideal Water Quality Model Approach

There is currently no single modeling framework that can simulate hydrology and water quality conditions at the field scale with the ease of use and accuracy necessary for a non-expert to use as a metric. This is not surprising given the variability in objectives and supporting data that serve as the foundation for existing field and watershed scale models. Because each model has relative strengths and weaknesses, it is informative to compare existing models to an "ideal" model that has all the necessary capabilities for a metric:

- Supported by reputable data and databases that inform the field scale processes that are represented in the model; and
- Provides the capability to accurately represent landside properties and best management practices, and can accurately predict water quality outcomes resulting from conservation practices throughout the U.S.

Specific characteristics of the idealized model were developed and organized into categories based on the following questions:

- What are the **general characteristics** of an ideal model?
- What **spatial resolution** should be represented in the ideal model?
- What **model processes** would be represented in the ideal model?
- What **land management capabilities** would be represented in the ideal model?

The specific characteristics outlined below serve as the basis for assessing the individual models.

General Characteristics:

The ideal field scale model should include the following general characteristics:

1. Temporal resolution based on a suitable time step (daily or finer);
2. Broad applicability to U.S. regions and associated crop types and cropping patterns;
3. Capability to conduct simulations at a field scale within a reasonable timeframe (i.e., suitable computational efficiency); and
4. Transparency, in the form of readily available documentation/support and diagnostic capabilities to elucidate and troubleshoot model results.

Spatial Resolution:

Spatial resolution refers to both the degree of horizontal segmentation of a field and the fineness of the vertical segmentation of the soil column. The resolution of the horizontal segmentation may be important for fields that have, for example, heterogeneous soils and/or topography. The vertical segmentation of the soil column affects the capability of the model to represent tillage activities and fertilizer application/integration in the soil. The ideal field scale model will include the spatial resolution characteristics listed below.

1. Horizontal representation:
    a. Multiple model segments are possible (based on either a gridded layout or areas that share common characteristics)
    b. Segment delineation appropriately captures in-field topography, soils and land use/cover
    c. Routing of water and water quality constituents between model segments can be represented
2. Vertical representation:
    a. Overall depth of soil profile is represented by the model
    b. Soil layer resolution (i.e., depth intervals) is sufficient to capture gradients in soil moisture and nutrients caused by tillage and other management activities
    c. Soil properties (e.g., density) can vary by layer

Model Process Representation:

The ideal field scale model will include equations that can realistically simulate the movement of water through all important pathways (hydrology), as well as the associated movement and fate of sediment, nutrients (including nitrogen and phosphorus), and pesticides. In addition, the ideal model will explicitly represent plant growth and the influence of this process on both hydrology and nutrient cycling. Finally, the model must be capable of representing best management practices (BMPs) via changes to the cropping system or other aspects of field management for the purpose of reducing pollutant loads. The specific process capabilities of the ideal field scale model are outlined below:

1. Hydrology:
    a. Representation of multiple pathways for water to move from the field (tile/surface/lateral/deep groundwater), as well as key pathways of water movement through the soil matrix
    b. Explicit tile drain representation (BMPs can include surface to tile connections and drainage water management)
2. Sediment:
    a. Sediment runoff that accounts for sheet, rill, and ephemeral gully erosion and in-field deposition
2. Nutrients:
    a. Representation of both total nitrogen and total phosphorus as well as the individual components of the total nutrient concentration
    b. Representation of multiple pathways for nutrients to move from the field
    c. Representation of nutrient cycling (including plant residue, carbon accounting, etc.)
3. Pesticides:
    a. Representation of multiple pathways for pesticides to move from the field
    b. Representation of pesticide degradation and plant interactions
4. Plant Growth:

   a. Plant growth represented and linked to the hydrology and nutrient cycles
   b. Plant density and survivability

Land Management Capabilities:

The ideal field scale model will include the capability to represent various land management actions/conditions, including implementation of these actions at the daily time scale. Specific management actions supported by the model would include:

1. Fertilizer applications (including specification of quantity, timing, depth, and type);
2. Tillage actions (including specification of timing, type, depth, and associated changes in field infiltration characteristics);
3. Irrigation actions (including flood irrigation with ponding);
4. Crop planting and harvesting operations; and
5. Best management practices (both structural and practice-based).

The ideal model should represent all practices of interest, including those implemented within the field (e.g., cover crops, reduced tillage) and at the edge of field (e.g., filter/buffer strips, wetlands).

Existing Water Quality Modeling Approaches

Fourteen field scale and watershed scale modeling frameworks were evaluated and compared to the "ideal" model described in the previous section. The models selected were those that were identified as the most likely to be appropriate for quantitative water quality evaluations at the field scale, and include both process- and index-based models. Process-based models generally use a combination of mechanistic algorithms and empirical relationships to quantify water flow and pollutant loading along hydrologic pathways. These models may require some amount of calibration based on the location or dataset being used. Index-based models, on the other hand, are based a higher-level empirical approach that relies on a relative rating of water quality conditions based on field characteristics and management conditions. They generally do not require calibration.

A high-level summary of each water quality model is provided below, followed by a ranking of key characteristics (Table 1). These summaries do not capture all of the important details for each model; rather, they are intended to provide a bottom line assessment of the applicability and usability of the model for simulating water quality conditions at the field scale. An aggregate assessment of existing water quality model capabilities and supporting monitoring data is provided in the "Challenges and Gaps in Quantifying Conservation Outcomes" section.

INDEX BASED MODELS

STEP

The *Stewardship Tool for Environmental Performance (STEP)* index model provides the water quality components for the larger *Resources Stewardship Evaluation Tool (RSET)*. RSET is a USDA developed, web-based tool which provides consumers the opportunity to modernize their conservation planning and assist in identifying goals and improving outcomes. This model operates on a planned land unit (PLU), such as a field, and is based on models already widely in use throughout the NRCS. Users are asked a wide variety of questions regarding cropping rotations, yield, tillage type and timing relative to planting, application methods and rates for both nitrogen and phosphorus fertilizers, and integrated pest management practices. Users also have the opportunity to further personalize their results by providing their soil test phosphorus results and selecting from a list of cover crop types. Using nutrient management as an example, PLUs are evaluated for total phosphorus loss, soluble phosphorus loss, nitrogen loss to both surface and groundwater, and nitrogen loss to the air using a points system. These scores are then compiled and compared to a benchmark applicable to the PLU being analyzed.

WQIag

The *Water Quality Index for Agricultural Runoff (WQIag)* was specifically developed by researchers at the USDA Natural Resources Conservation Service to give farmers and ranchers a simple way to quantify the management and physical conditions of their fields relative to potential water quality impacts. Producers can enter their fertilizer applications, pest management, tillage practices, conservation practices, and irrigation/drainage information. The index also accounts for simple physical characteristics that can be identified through the Web Soil Survey platform. Once data entry is complete, the producer receives a single rating on a 1 to 10 scale that shows how their field stacks up. Because this is an index model, the results do not specify an absolute loading, which makes this model unsuitable for applications where specific reductions (for example, lbs/acre) are required.

PROCESS BASED MODELS

The modeling frameworks described below represent field scale models unless they are specifically noted as “watershed models.” Note that the individual descriptions provided below include references to other process-based models included in this section; the introduction and descriptions for those models may occur either before or after they are referenced.

APEX

The *Agricultural Policy/Environmental eXtender Model (APEX)* is maintained and distributed by Texas A&M AgriLife Research. It was originally developed to extend EPIC’s capabilities on small watersheds and farms. Within the model are components for hydrology, water quality, pesticide, and sediment predictions across complex landscapes consisting of land areas that are segmented to be relatively homogeneous in regards to climate, management, soils, and slopes. APEX is well documented, the subject of many peer reviewed articles, and has many output variables which support diagnostics.

AnnAGNPS

The *Annualized Agricultural Non-Point Source (AnnAGNPS)* watershed model provides roughly similar capabilities to SWAT in terms of simulating agricultural landscape processes, including explicit representation of crop growth and a detailed treatment of agricultural management (planting, harvest, tillage, fertilization, etc.). A wide variety of crops can be simulated and individual land response units are represented, with the horizontal resolution scalable.

CREAMS

The *Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS)* model was developed by research scientists at the USDA-ARS and dates back to the 1970s. It is the predecessor to the GLEAMS model and as such is generally no longer used in new research studies. CREAMS contained algorithms for limited simulation of hydrology, pesticides, nutrients, and sediment over a single land use with homogenous soils and management.

DRAINMOD

DRAINMOD was developed by researchers from North Carolina State University and is used to model subsurface drains. The most recent version allows for the simulation of nitrogen transformation and fate. Outside research groups have developed modules for phosphorus. Simulations are run using a one-dimensional, vertical column and water balances can be viewed at both an hourly and daily time scale. Online documentation for version 6.0 of the model is available from North Carolina State University.

EPIC

Like APEX, the *Environmental Policy Integrated Climate (EPIC) Model* is maintained and distributed by Texas A&M AgriLife Research. It is capable of simulating a wide variety of crop rotations, tillage systems, and management practices. Algorithms include those necessary for simulation of hydrology, nutrient transport, carbon cycling, plant growth, and erosion. The model runs at a daily time step and it has been used in applications over much of the United States.

FHANTM

The *Field Hydrologic and Nutrient Transport Model (FHANTM)* is a field scale model that used algorithms from DRAINMOD and GLEAMS to simulate hydrology and nutrient transport in the high water table environment of Florida. Unlike the official release version of DRAINMOD, FHANTM includes the ability to predict phosphorus transport. While the model has been tested in many cases for fields in Florida, applications outside of Florida have not always succeeded in accurately predicting measured data.

GLEAMS

Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) is a field scale model originally developed as an extension of the CREAMS model. Four major constituents are predicted: hydrology, sediment, nutrient transport, and pesticide transport. The model assumes the field contains homogeneous land use and soils and only allows for a single precipitation input. It is capable of estimating the impacts differing management systems (including tillage systems, irrigation changes, etc.) can have on nutrient and pesticide transport. The GLEAMS FORTRAN source code, executable code, parameter editors, sample data, and supporting documentation are available at no cost from the developers.

HSPF

The *Hydrological Simulation Program – FORTRAN (HSPF)* watershed model provides a proven and flexible framework for simulating watershed landscape hydrologic and water quality processes. HSPF, which was developed under EPA funding, has been successfully applied to a wide variety of watershed conditions and is capable of representing advanced nutrient processes. However, the model is not well-suited to simulating agricultural field scale conditions because it does not explicitly represent crop growth or key management events such as tillage and fertilizer application. These processes can only be indirectly represented by modifying model input parameters (e.g., soil properties).

MIKE-SHE

MIKE-SHE is a proprietary model developed and maintained by the Danish Hydraulic Institute (DHI). Access to this program must be purchased from the developers; several licensing options are available. It represents all major processes in the hydrologic cycle and is capable of simulating the transport of water and solutes through the soil. This model is flexible enough to simulate various spatial scales, from single soil profiles to large watersheds. It additionally has the capability to simulate pesticide transport and erosion. It is frequently combined with DAISY, a detailed soil-plant atmosphere model, when used in agricultural applications and add-on modules are available from the developer to enhance simulation of agricultural practices.

RUSLE2

The *Revised Universal Soil Loss Equation 2 (RUSLE2)* is a field scale erosion model supported by the USDA-ARS. It is capable of estimating the rill and interrill soil erosion that is caused by rainfall as well as the associated overland flow. It operates independently of land use as the model utilizes very basic plant features such as yield, canopy, rooting patterns and surface roughness. The NRCS has developed management descriptions for many crop management systems over the United States and, as such, the model is highly flexible regarding the geographic areas it can represent.

RZWQM2

The *Root Zone Water Quality Model 2 (RZWQM2)* includes algorithms for major physical, chemical, and biological processes relevant to agricultural crop production. While it is generally a one-dimensional (vertical in the soil profile) process-based model, it is capable of simulating lateral flow and flow through tile drainage systems. Within the root zone of the unit of area being modeled, the model simulates plant growth and the movement of water, nutrients and pesticides. Agricultural management practices available include planting and harvest practices, various tillage systems, manure and chemical nutrient applications, and irrigation events.

SWAT

The *Soil and Water Assessment Tool (SWAT)* watershed model was developed and is currently supported by the joint efforts of the USDA Agricultural Research Service and Texas A&M AgriLife Research. The model’s code is in the public domain and it is the topic of more than 2,000 journal articles. Though it is typically employed at the scale of a watershed, the base units of the model are suitable for field scale modeling as they represent unique combinations of soils, slopes, and crops. SWAT is capable of representing a range of agricultural crops and management conditions and provides outputs for hydrology, nutrients, sediment, and pesticides at a daily time step.

Comparing the Models

Each of these models was evaluated relative to the characteristics outlined for the idealized field scale model in the previous section. A color-coded matrix was developed to provide a qualitative ranking for each model relative to each characteristic (Table 1). For most characteristics, the models are rated as high (“H” - blue), medium (“M” - green), low (“L” – light yellow), or not applicable (“NA”) with respect to how well they meet the target specifications for a characteristic. In some cases, a designator of unknown (“UK”) is shown if the documentation was not clear or insufficient in a particular area. For temporal characteristics, the models are denoted as daily (“D” – blue), monthly (“M” – green), or annual (“A” – light yellow), with the daily timescale representing the target capability. A more detailed description of the rating system applied for each individual characteristic is provided in Appendix A and a list of the references used to describe the models is given in Appendix B.

Table 1. Summary of Water Quality Model Characteristics

	Index Based Models		Process Based Models											
	STEP	WQI	AnnAGNPS	APEX	CREAMS	DRAINMOD	EPIC	FHANTM	GLEAMS	HSPF	MIKE-SHE	RUSLE2	RZWQM2	SWAT
MODEL USABILITY														
Ease and Efficiency of Use	H	H	M	L	L	L	M	UK	L	M	M	M	L	M
Crops modeled	H	M	H	H	H	UK	H	UK	H	L	UK	H	M	H
Time Step	L	L	H	H	H	H	H	UK	H	H	H	H	H	H
Transparency	L	M	M	M	M	M	M	L	M	H	L	M	L	H
Applicability across the US	H	H	M	H	H	H	H	L	H	H	H	H	UK	H
Horizontal Segmentation	L	L	M	H	L	L	M	UK	M	M	M	L	L	M
Vertical representation	L	L	M	H	M	H	H	H	H	M	M	H	H	H
MODEL PROCESSES														
Edge-of-Field BMPs	UK	L	L	H	L	UK	UK	UK	M	M	UK	M	UK	H
In-Field BMPs	L	L	M	H	M	UK	H	UK	M	L	UK	M	UK	H
Hydrology	L	L	M	H	M	M	M	H	M	M	H	M	H	H
Irrigation	L	L	H	H	NA	M	M	UK	M	H	H	M	M	H
In-Field Management Options	L	L	H	H	M	M	H	UK	H	M	M	H	H	H
Nitrogen, Phosphorus	M	L	H	H	M	L	H	L	H	H	M	NA	L	H
Pesticides	L	L	H	M	H	UK	H	UK	H	H	M	NA	H	M
Plant Growth	L	L	H	H	H	M	H	M	H	L	L	M	H	H
Sediment	L	L	H	M	M	UK	M	UK	M	H	H	H	NA	M
Tillage Options	M	L	H	H	H	M	H	UK	H	L	UK	H	H	H

MEASURING WATER QUALITY IMPACTS OF CONSERVATION PRACTICES

Background

While watershed and field scale models can serve as useful tools for assessing the water quality impacts of conservation practices, constructing these models requires detailed knowledge concerning the physical characteristics of the field. Usually this information includes the soils, the slopes, and the land cover for the area to be simulated. For models in the United States, these items are easily obtained from commonly available geospatial layers such as the SSURGO soils layer, the National Elevation Dataset, and the Cropland Data Layer. Datasets available from the NOAA National Centers for Environmental Information provide rainfall and temperature data to drive the climatic process of the model.

Although describing these physical characteristics in the model framework is an important first step, it is also important to verify the performance of the model's predictive ability for the agricultural field conditions of interest ("calibration"). This requires far more information about the outcomes - including measurements of actual water quality that can be compared to model estimates. At the watershed scale, this additional information can come from many commonly available sources such as surface water flow and water quality data from the U.S. Geological Service, county average crop yields reported by the USDA-ARS, and field management templates from local land grant universities or conservation groups. When working at the field scale, the model needs very detailed information about field management schedules and any existing BMPs, along with sufficient field collected water quality data to support calibration. This section explores current water quality data collection programs to assess relevance for field-scale model development, and identify gaps.

Status and Gaps in Monitoring Data

Key questions that must be asked with respect to monitoring programs conducted at the field scale include:

- What is the overall extent and status of existing monitoring programs being conducted at the field scale?
- What are the critical data gaps that can be identified based on knowledge of previous and current field scale monitoring efforts?

These two questions are addressed in the following sub-sections.

Status of Ongoing Monitoring Programs

The type of data required to calibrate a field scale, process-based model can be difficult to obtain, as there are only a limited number of fields that have been instrumented and documented (when compared to the relative richness of measurements of water quality in-stream). Researchers at various universities, the USDA-ARS, conservation groups, and some grower groups generally carry out the process of collecting data. While there are 'drops' of field scale data available across the body of peer-reviewed literature, a few programs stand out for systematically collecting large quantities of data suitable for this type of modeling.

The Discovery Farms program was created by researchers at the University of Wisconsin and was patterned off water quality research studies in the Netherlands. The program has been operating in Wisconsin for the past 15 years and has expanded to include Arkansas, Minnesota, and North Dakota. These programs work with livestock and crop farmers to measure surface flow, tile flow, nitrogen and phosphorus exports, sediment and other parameters. The program is funded by a variety of state and federal agencies as well as extension agencies, grower groups, foundations, and private industry.

Most of the Discovery Farms programs are still in operation and data can be accessed through a USGS portal or by reviewing the summaries provided on the program website. In Arkansas, the farms are designed to operate for five to seven years. Farm profiles and annual reports are posted on the program website [1]. Wisconsin Discovery Farms has past and current projects in more than 20 counties in Wisconsin. The program includes six producers collecting field data of the type useful for calibrating field scale, water quality models of row crop lands. In Minnesota, monitoring data have been collected from fields since 2011. The Minnesota 2017 Work Plan indicates that three farms will be heading into their seventh year of data collection, while the other farms have been active for 3-5 years. Real time data for twelve fields are available from their website [2].

Dr. Kevin King (USDA-ARS) leads a research group that studies paired farm fields in northwest Ohio growing corn, soybeans, and wheat. Fields are instrumented so that data can be collected describing flow and nutrients over the land surface and in tile drains. Research in this program is ongoing; new fields were added in 2016, and new BMPs will be added after the field baselines are established. This research spans multiple counties and cropping systems common across this region of Ohio. The Minnesota Corn Growers Association funds third-party research studies focusing on water quality. Research covers topics such as cover crops, nitrogen application timing, and tile drainage. In the Great Lakes region, the USGS is monitoring edge-of-field sites in several priority watersheds spanning Ohio, Indiana, Michigan, New York, and Wisconsin [3]. An overview of these and other programs is provided in more detail in Appendix C. It should be noted that this commentary and the associated appendix do not constitute an exhaustive review of these types of programs and others may exist or be in formation which are not mentioned here.

In addition to these multi-farm projects, there are a number of university and USDA researchers working on single field sites. Since 1996, Dr. Dan Jaynes of the USDA-ARS has collected tile drain nitrate and discharge data at a study site in Iowa [4]. Dr. Matthew Helmers in the Agricultural Water Management research group at Iowa State University has completed work at the plot scale studying subsurface drain flow [5].

Critical Gaps

Even within these multi-site programs, there exist gaps between the data types required to support modeling for an entity like Field to Market (which represents diverse growers using a wide range of management actions and BMPs) and the measured data which are available. To illustrate, the crops and practices on the study farms from one Discovery Farm program are listed in Table 2. These farms provide data for a variety of crops and a variety of BMPs. However, when cross-referencing the available field data with all potential combinations of crops and BMPs (Table 3), it is apparent that there are clear gaps in the data that need to be addressed in order support understanding of the behaviors of specific BMPs for specific crops. While both wheat and conservation tillage are represented in the program, there is no one field where both practices are tested together. Therefore, a modeler would not be able to calibrate a model to test the outcome of conservation tillage on a wheat field based on data available from this program. For this reason, it is not sufficient to report crops and BMPs at a program level as this may mask gaps that are present at the field level.

Table 2. Example of crop/BMP combinations from one sampling program

Program	Field	Crops	Best Management Practices Examined
Arkansas Discovery Farm	ARK1	corn, soybean	cover crop, conservation tillage
	ARK2	soybean, wheat, rice	switchgrass buffer
	ARK3	rice, corn, soybean	irrigation management
	ARK4	cotton, corn	conservation tillage
	ARK5	rice, corn, soybean	cover crops, nutrient management, irrigation management
	ARK6	rice, corn, soybean	cover crops, nutrient management
	ARK7	rice, corn, soybean	cover crops, nutrient management, irrigation management

Table 3. Availability of field sampling program data for combinations of crops/BMPs

	Cover Crops	Grassed Waterway	Buffer Strip	Conservation Tillage	Nutrient Management	Saturated Buffers	Wetlands
Corn	++	0	0	++	++	0	0
Wheat	0	0	+	0	0	0	0
Soybeans	++	0	+	+	++	0	0
Cotton	0	0	0	+	0	0	0
Potatoes	0	0	0	0	0	0	0
Rice	++	0	+	0	++	0	0

++: Combination assessed at multiple fields +: Combination assessed at single field 0: Not assessed

While the previous tables illustrate the issue of gaps at the program level, reviews of the literature have identified the following gaps and challenges related to field scale data at the national scale:

- Field scale data focused on potatoes as a crop are difficult to find.
- Much less data are available in the Western states than in Corn Belt and Mid-South states.
- Much of the published literature focusing on field collected data relies on plot scale[1] data collection. It is difficult to identify studies on fields at least 1 hectare in size.
- Study sites with tile drains often only monitor drain flow and not surface flow. This makes partitioning between surface and tile flow difficult.

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[1] Used here, plot scale generally refers to an area much smaller than a typical agricultural field. A study conducted on a space of land sized 10 meters by 30 meters would be considered 'plot scale'.

- In many cases, management data are not sufficiently detailed to properly parameterize the cropping section of the model.
- In many cases, field studies monitor only nitrogen, phosphorus, or sediment; rarely do they report on all three pollutants.
- Temporal resolutions are sometimes large, such as annual or even multi-year averages. In general, a model is considered more robust if calibrated with finer resolution data. In addition, many studies take place for only one or two years. Long-term datasets are of the greatest value, as they can be leveraged to improve the representativeness of the model across a wider range of field and climate conditions.

For the field scale data that do exist, there is also a lack of standardization in reporting, which can make it difficult for modelers to efficiently use the results of past studies. The following information is needed in order to use the results of a field study to support a modeling analysis:

- Exact location of the field: Identification of the field is necessary for parameterizing the model with appropriate soils and slopes. If this information is withheld for grower privacy reasons, detailed characteristics of the field can be reported including the area of all soil types, the presence of field buffers, and the dominant slopes in the field by soil type.
- Presence of tile drains: An absent/present marker is helpful, but it is also important that the depth and spacing of the tiles be reported, as these parameters can significantly affect the overall hydrology of a field.
- Detailed management data: Since many of the process-based models are capable of real date scheduling, researchers should report a table of management actions on the field which include the action date and specific information such as amount of fertilizer applied, type of fertilizer, type of tillage implement, harvest yields, planting particulars, and any BMPs implemented. If the BMPs are not structural or require hands-on management (such as drainage water management), information should be provided on how they were managed.
- Units of reported constituents: Researchers report results using a variety of units; concentrations, total annual loads, and unit-area loads are all common. While all these formats are useful, for most of the models reviewed here, comparisons would be the most direct if the literature reported unit-area loads or total loads along with the exact size of the field.

Field Scale Databases

The Measured Annual Nutrient loads from Agricultural Environments (MANAGE) database [6] contains ample literature covering field scale data collected in over 30 U.S. states and Canadian provinces. These states range west to east from California to Florida and north to south from Minnesota to Texas. Originally released in 2006, updates to the database have been released as recently as 2016 [7], [8]. Each reviewed paper was documented and the water quality constituents were logged along with information about the study. Data gaps in the reviewed studies were typically related to identification of field location and field size. Larger fields tended to lack suitable spatial information, while fields with good spatial detail tended to be very small research plots. Comparison across studies is difficult as researchers often reported different constituents, units, and time steps.

In addition to the MANAGE database, there have been several meta-analyses of literature supported by the International Plant Nutrition Institute and the 4R Research Fund. One project reviewed the impact of various management techniques on nitrous oxide and nitrate losses from corn fields [10]. Approximately 400 observations of nitrate leaching losses were recorded. A second review, comprised of studies from 11 states, completed a meta-analyses on literature that included phosphorus surface loss as it related to fertilizer placement and tillage [9]. Finally, work using the MANAGE database was completed to quantify phosphorus loss reductions as they relate to BMPs [11].

CHALLENGES AND GAPS IN QUANTIFYING OUTCOMES

The previous sections characterized and contrasted available field scale and watershed models, and highlighted how even well-designed and comprehensive monitoring programs do not address all cropping system/BMP pairings. A discussion of the primary gaps that inhibit the ability to predict water quality outcomes of specific practices follows.

Technical Gaps in Models

Water quality models are mathematical tools describing our best understanding of the relationship between land use and water quality outcomes. Models are merely simplified mathematical descriptions of a complex real world. They do not create new data; rather they serve to integrate existing data in a structured manner consistent with our best understanding of environmental processes. As such, models are only as good as the data upon which they are based. Many factors (e.g., agricultural practices, climate, soil type, topography, BMP type, BMP implementation approach) influence the relationship between land use and water quality outcomes. Myriad combinations of these factors exist across the country, and field data capable of describing water quality impacts exist for only a small subset of these combinations.

In one way or another, all of the models reviewed here fell short of the idealized field scale model discussed in Section 2. Technical gaps include model configuration, computational limitations, limits imposed by the structure of the model code, and other factors. One example of a systematic technical gap is that many models do not allow routing between land units before the water leaves the field. This hampers the model's ability to accurately predict in-field transport of water and associated constituents, which can be very important in fields that are even slightly sloped. Effort is being expended to fill this gap; as an example, SWAT researchers are working on a version of the model called SWAT+ that will allow elements of hydrology and water quality to be routed between landscape units before being routed to the nearest channel [12].

As can be seen from the "unknown" (UK) entries in the modeling matrix (Table 1), transparency is a common gap for many of the models reviewed here. While some models have comprehensive, single-source documentation, many require multiple sources (including items released by the developer as well as peer-reviewed literature from academia) to answer questions about the model's capabilities. There is some distinction between the level of documentation suitable for researcher-users of the models and practitioner-users of the models. A practitioner-user like Field to Market requires clean, easily digested documentation that is accessible and comprehensive. A researcher-user may be less inconvenienced by documentation that is spread out over several sources.

Another gap identified across the process-based tools reviewed is ease and efficiency of use. These tools generally require a significant investment of time and effort as well as knowledge of the correct parameterization methods and multiple iterations to reach a suitable outcome. Web tools are seeking to fill some of the technical gaps related to user-friendliness and input processing. Recent work has produced the Nutrient Tracking Tool (NTrT), a web-based tool developed by the USDA and linked to the APEX model [13]. While this tool surmounts some of the hurdles related to usability, challenges remain with regional parameterization [14]. NTrT and other tools like it highlight the research movement towards developing regional parameter sets and the capability to apply process-based models across a variety of field conditions while minimizing the effort required.

While some modeling gaps are a result of technical challenges, other gaps are caused by a gap in current research or understanding of detailed processes at the field scale. As an example, many models are still using the SCS CN approach as a method of addressing hydrology where data are lacking. This methodology can muddy the real reaction of the field surface to management actions (such as tillage).

Some gaps may be the result of both the technical challenge of getting the process into the model and the limited research with which to develop the equations. Edge-of-field BMPs were a frequent gap identified for the models. While research in this area is ongoing and there is already a large body of work available, challenges remain with coding detailed representation of the processes (via a set of algorithms or parameters) into the models. New and emerging research in this area may make it challenging for model developers to keep up with the newest forms of BMPs or there may be a lag in the time between a BMPs popularization within the producer community and the availability of research data to parameterize its behavior. Because edge-of-field practices are an important component when seeking nutrient reduction at a watershed level, when gaps are encountered they should be detailed by asking if the gap is present due to a gap in the model coding which restricts implementation, the "newness" of the method, or a lack of research which supports quantification of benefits.

Technical and Practical Challenges

A wide range of models exist with various areas of focus and none are universally applicable. While useful pieces of model algorithms may be present over several different models, it is technically challenging to migrate pieces of one model to another model given potential differences in code, decisions made by the original developer, lack of commentary describing coefficients and other factors. In addition, there is a variety of complexity represented over the modeling space and the algorithms in watershed/field scale models tend to be very interdependent. Development of new models, or combinations of existing models, are therefore very complex, time consuming efforts.

Additional challenges exist when collecting the data required to test and verify model performance. Water quality sampling is still moderately complex and expensive. Data to support model development should ideally be available for frequent intervals to capture important time dynamics, and at both the field and watershed scale. As many researchers can attest, field data collection is frequently an imperfect process. Data are affected by extreme field conditions (such as flooding), field management activities change expected data availability, data-loggers go offline and data are lost, and participating producers may have to make unplanned changes to their management approach to accommodate weather extremes or market conditions. Whether working within the context of a single field or across a broader area, the following questions should be considered and addressed when designing (or modifying) a monitoring program to support a field scale modeling effort: How much data do I need in each area I want to represent? How should the data I collect be distributed across that area? How much geographic area can one parameter set be reliably expected to represent?

Skill Level of Model Applications

Process-based models require a certain element of calibration to improve the accuracy of their results. In some cases, this can be as simple as reasonably parameterizing the soils, while other models have hundreds of potential parameters. Some models contain parameters that are not physically based, making it difficult to perform regional reviews of calibrated models and arrive at a working set of parameters. This is due to the fact that researchers are distributed over a wide variety of institutions and have differing priorities in mind when calibrating. Auto-calibration techniques and tools have made it feasible to achieve a calibration that looks excellent for one field or watershed from a performance standpoint while having low applicability to other sites. All these factors can make it difficult to perform straightforward literature reviews and identify suitable parameters, i.e. "crowd-sourcing" a good regional parameterization.

It is important to recognize that it will not be practical to specifically calibrate a model to the precise physical and management conditions for every field. This is due to two primary constraints: 1) site-specific data are not available for every field, and 2) resources to conduct a modeling effort are typically limited. Therefore, when considering the overall skill of a model, it is important to evaluate whether the model is capable of reproducing observed flow and loading data without requiring site-specific calibration, based on appropriate regional input parameters and local slope and soils information.

Communication Needs

Model predictions are inherently uncertain, yet they often provide the best available understanding of water quality outcomes based on a synthesis of available data. It is important to communicate this uncertainty, and the value of models as educational tools should be stressed. This is an area where index models have an advantage over process-based models, as they are generally easier to understand and interpret. However, even with a process-based model, it is usually possible to diagnose why the model produces a particular result and then develop a clear explanation for that outcome (i.e., relating it back to management approach or field conditions). Communication of findings from a field scale model application can also benefit from conducting sensitivity simulations with the model. Such simulations evaluate "what if" scenarios that represent a modified management approach or field condition relative to the actual conditions and can provide valuable insight and context for the original/baseline results.

Consideration should also be given to how to present results given model uncertainty. For example, it may be helpful to present a variety of scenarios as a list of management activities that could be changed, divided up into those that are likely to be net-positive and those that are likely to be net-negative given the resource concern being addressed. These types of comparisons are more difficult with index models than with process models. For WQI, as an example, users can not simulate instances where no-till would be net-negative because it is an index model, and this management action is always represented as a net-positive. A process-based model is needed to capture these kinds of differences.

RECOMMENDATIONS

Significant progress has been made to improve model capabilities and expand field scale monitoring programs, but challenges to a robust, field-scale quantitative metric remain.

Recommended improvements to field scale models include:

- Model developers should strive to increase transparency of their models by improving and consolidating their documentation materials. These materials should be kept up to date with respect to the latest model version and be upfront about the model's capabilities.
- Ease and efficiency of use will increase as modelers move to integrate their models directly with online databases, decreasing input processing time. For example, integrating a field scale model with web-accessible digital elevation model and detailed soils information map would significantly reduce the effort required to configure a model application.
- Representation of BMPs (both in-field and at the edge-of-field) should be expanded. Some of the gaps identified in BMP representation may be remedied with better documentation, but for gaps in technical implementation, development should focus on flexible frameworks that are backed by robust data collected through literature, direct field monitoring, and/or knowledge of system function.
- Routing of water, sediment, and nutrients within a field should be represented in greater detail.

Recommended improvements to field scale monitoring programs include:

- Funding agencies should request that researchers seek to adhere to a form of standardization in reporting their results.
- Monitoring programs should report their crop system/BMP matches in the most accurate way their producer-privacy agreements allow. Reporting detailed field management information will allow new research to be developed that can specifically target gaps in these combinations.
- Geographic areas of study should be expanded. At the current time, it would be difficult to support a nation-wide metric with the available field scale data because not all cropping regions are equally represented. Research in the MANAGE database shows gaps present in states like Pennsylvania, Idaho, Tennessee, and many of the western states [8], [15], [16].
- Monitoring efforts should be focused on using realistically sized fields (> 1 hectare), where possible. Partnerships with both producers and university research farms will be important in this area. This will allow for research that is more relevant to the program and being producer-integrated will help the data collection program stay abreast of new techniques and applications.
- Careful thought should be given to the temporal resolution of the data collected and the length of time sites stay active. Established sites are valuable because long-term data collection allows for the comparison of practices given constant soil and landform conditions. Daily data are important because previously collected research has established that single day events can be essential to overall annual loads and ecologic outcomes in the surrounding watershed.

While these recommendations can eventually lead to the modeling proficiency and data availability necessary to develop a field scale water quality metric founded on a process-based model, achieving that aim at a national scale (while representing the water quality outcomes of all farm fields with equal skill) is not yet possible. However, models are valuable tools and even without comprehensive data coverage, progress is being made toward better understanding of the systems they represent and the linkage between practices and outcomes. Model applications are also useful in identifying broad and specific data gaps and can help guide monitoring to address those gaps. Much can be accomplished through the use of index models as well as strategic use of process-based models where sufficient data and information exists.

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APPENDIX A: RATING SYSTEM FOR FIELD SCALE MODELS

	High	Medium	Low
MODEL USABILITY			
Ease and Efficiency of Use	Model is supported by sufficient databases to standardize soils, tillages, fertilizers, crops, and pesticides which the researcher can use to create the model. The model has an accessible interface with clear instructions.	The model is database supported and comes with reasonable defaults for many, if not all, of the required parameters. The interface may be difficult to access and/or the user may have to work with the model outside of the interface.	The user must configure unique values for each application. There is no interface for model development or running the model.
Crops Modeled	All crops used by Field to Market members plus those needed to model conservation practices	The available crops represent only a few of Field to Market's crops of interest or there are significant gaps in the models ability to explicitly model crops or conservation cover.	Only one or two crops are available and there is no method for adding new crops or implicitly representing crops via parameter adjustment.
Time Step	Daily or finer	Monthly, seasonal, or real annual	Average annual
Transparency	Support/documentation easily available on model website (which is easily found by searching). Model has diagnostic capabilities.	Support/documentation easily available on model website (which is easily found by searching) OR the model has diagnostic capabilities.	Model is difficult to diagnose and the documentation/support are both lacking in quality/quantity/ease of use.
Applicability across the US	Useful in all lower 48 states	Useful in one cropping region (about the size of a HUC02)	Only useful in one or a few states
Horizontal Segmentation	Multiple model segments are possible (either gridded or characteristic-based) Segment delineation appropriately captures in-field topography, soils and land use/cover Routing between model segments can be represented	Multiple model segments possible, but no ability to route from land segment to land segment	A single segment or point
Vertical Representation	Overall depth of soil profile represented by model Soil layer resolution (i.e., depth intervals) that can capture tillage and management effects	There are 2 soil layers, a surficial layer and a subsoil layer	Only one layer is represented or all soils in the model are represented by a few key characteristics (such as K-factor or HSG)

	High	Medium	Low
	Soil properties can vary by layer		
MODEL PROCESSES			
Edge-of-Field BMPs	The model has the mean to mechanistically simulate a variety of edge of field BMPs by adding their physical characteristics into the model framework. Those characteristics are allowed to influence model hydrology and nutrient/pesticide transport.	Explicitly represented but not as many options, or reductions are done by regression based equation. Implicit representation if few parameters need manipulating	Representation either requires heavy manipulation of parameters or is just a straight percent reduction
In-Field BMPs	A wide range of in-field BMPs which can include explicit management actions and alternate pathways such as surface to tile connections and/or drainage water management. Cover crops can be grown explicitly. Conservation tillage can be explicitly included.	Explicitly represented but not as many options or reductions done by regression based equation. Implicit representation if few parameters need manipulating	Representation either requires heavy manipulation of parameters or is just a straight percent reduction
Hydrology	Representation of multiple pathways for water to move from the field (tile/surface/lateral/deep groundwater/shallow groundwater) as well as key pathways of water movement through the soil matrix. There is explicit tile drain representation	One of the key pathways is missing or the model doesn't explicitly represent tile drains	The model includes logic for how water should be partitioned between infiltration and runoff, but no pathways are represented explicitly. This could be ratings-based or a simple estimate.
Irrigation	Irrigation water can come from multiple sources (groundwater, stream, etc.). It can be applied manually or via soil water deficit. The irrigation module can be constrained using modeler knowledge of irrigation norms for their site. Irrigation BMPs can be included and/or the type of irrigation (sprinkler, drip, center pivot, and flood) can be specified.	Can represent explicit irrigation via water addition to the landscape and removal from one or more sources within or outside of the watershed.	Takes absence/presence of irrigation into consideration
In-Field Management Options	Fertilizer (amount/timing /depth/type), tillage actions (timing/depth/type/changes in field infiltration characteristics), irrigation actions (including flood irrigation with ponding), and	Date-based specification of management conditions possible, but representation is not explicit. The model user modifies parameters at a specific time to	No temporal resolution or user control of field actions, but the model can account for differences in tillage types/fertilization actions/etc.

	High	Medium	Low
	harvest & plant operations can be represented. Best management practices (both structural and practice-based) are available	implicitly represent actions on the field.	
Nitrogen, Phosphorus	Representation of multiple pathways for nutrients to leave the field. Nutrient cycling (including plant residue, carbon accounting, etc.) is included. There is representation of both total nitrogen and total phosphorus as well as their constituents.	Only simulates TP and TN, not the constituents of the nutrients (e.g., SRP, NO3). No crop uptake is represented. The model is missing at least one major transport pathway for nitrogen or phosphorus to leave the field.	The model takes nitrogen and/or phosphorus in consideration. One nutrient may not be simulated at all while the other is simulated at a medium or high level. The model may represent both nutrients but only in a simplistic way with no cycling or any explicit calculations.
Pesticides	There is explicit (such as movement from the field, washoff and degradation, and plant interactions) representation of multiple pathways for pesticides to move from the field. There is representation of pesticide degradation and plant interaction.	The model represents pesticides explicitly, but can only simulate one pesticide at a time or represents a single aggregate pesticide class.	Pesticides or pesticide management is included in the consideration of the final model outcomes, but pesticides are not explicitly simulated.
Plant Growth	Plant growth represented and linked to the hydrology and nutrient cycles. Growth is complex and may include concepts like plant density and survivability.	The plants grow on the landscape, but don't interact with either pesticides, nutrients, or hydrology.	Simplistic plant cover represented by month or by season.
Sediment	Sediment runoff that accounts for sheet, rill, and ephemeral gully erosion and in-field deposition	The model is missing ephemeral gully erosion, in-field deposition, or some other major component of sediment transport and fate, but sediment is explicitly represented in the model.	Non-mechanistic method of rating susceptibility to sediment erosion and washoff.
Tillage Options	Tillage operations are sufficiently explicit to occur at a user-specified date (and can occur multiple times per year), and include options which can represent the most common forms of tillage. A tillage operation is mechanistically used to mix soil materials and modify the soil surface, impacting both hydrology and nutrient/pesticide transport.	Date-based specification of tillage, but representation is not explicit. The model user modifies parameters at a specific time to implicitly represent actions on the field.	There is some way for modelers to differentiate between low tillage and intense tillage, but it is not date based or represented mechanistically by the model.

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APPENDIX C: EDGE OF FIELD MONITORING PROGRAM INFORMATION

Program	Location	Funded By:	Contact	Crop	BMP
Arkansas Discovery Farm	Arkansas	University of Arkansas, Farm Bureau Arkansas, NRCS, Walton Family Foundation, Arkansas Rice Check-off, Arkansas Soybean Promotion Board, USB, AR Natural Resources Conservation Service, AR Natural Resources Commission, AR Association of Conservation Districts, AR Corn and Grain Sorghum Board, Cotton Inc.	Andrew Sharpley & Mike Daniels	corn, soybean, wheat, rice, cotton, pasture	conservation tillage, cover crops, reduced tillage, switchgrass buffer, irrigation management, nutrient management, rotational grazing
WI Discovery Farm	Wisconsin	The State of Wisconsin and UW-Extension in addition to a number of annual grants from producer groups and federal partners	Eric Cooley & Amber Radatz, Co-Directors	corn, alfalfa, pasture, woodland, soybean, forages	conservation tillage, buffers, nutrient management, grassed waterway
MN Discovery Farms	Minnesota	Minnesota Agricultural Water Resources Center, Minnesota Corn Research and Promotion Council, Minnesota Soybean Research and Promotion Council, MN Dept. of Agriculture, NRCS	Tim Radatz, Discovery Farms Coordinator	corn, alfalfa, soybeans, sugar beet, dry bean, wheat	manure management, cover crops, conservation tillage, nutrient management, manure injection, incorporation of fertilizer, rotational tillage
Kevin King	Ohio	USDA	Kevin King	corn, soybeans, wheat	cover crops, nutrient management, conservation tillage, DWM
Missouri Corn Growers	Missouri	Missouri Corn, Syngenta, Environmental Resources Coalition, Missouri Dept. of Nat. Resources, USDA-ARS	Derrick Steen	corn	grass buffer strips, split applications, conservation tillage
Minnesota Corn	Minnesota, South Dakota	Minnesota Corn Growers Association	Jeff Vetsch, U of Minn.	corn, soybean	cover crops, nutrient management
North Dakota Discovery Farms	North Dakota		Ron Wiederholt	various	
Great Lakes Restoration Initiative, Edge of Field	Wisconsin, Michigan, Indiana, Ohio, New York	GLRI	Todd Stuntebeck, USGS	various	various