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An Approach for Estimating Water Quality Benefits of Conservation Practices at the National Level

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Abstract. *The United States Department of Agriculture has initiated the Conservation Effects Assessment Project (CEAP) to quantify the environmental benefits of conservation practices at the national scale. This paper provides an overview of the analytical approach being used in the CEAP national assessment to estimate off-site water quality benefits. For the assessment, a sampling and modeling approach is used. The farm-scale model Agricultural Policy/Environmental EXtender (APEX) is used to simulate conservation practices for cultivated cropland. Farmer surveys conducted on a subset of National Resource Inventory sample points provide information on current farming activities and conservation practices for APEX. Output from APEX will be input into the watershed scale model, Soil and Water Assessment Tool (SWAT) in the HUMUS (Hydrologic Unit Modeling for the United States) system for routing the pollutants to the 8-digit watershed outlet. SWAT will be calibrated and validated using the United States Geological Survey's SPAtially Referenced Regressions On Watershed attributes (SPARROW) model output, streamflow and pollutant data. The HUMUS system simulates in-stream effects for (a) a baseline scenario with conservation practices and (b) an alternative scenario without conservation practices. The off-site water quality benefits of conservation practices currently in use will be determined by comparing outputs for the alternative scenario to the baseline outputs at each 8-digit watershed. Benefits will be reported as reductions in in-stream concentrations and loadings of sediment, nutrients and pesticides, and reductions in the number of days that concentrations exceed human health and ecological thresholds.*

Keywords. Soil and Water Assessment Tool, Agricultural Environmental Productivity Extender, Conservation Practices, Water Quality, National Assessment, HUMUS.

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Introduction

The United States Department of Agriculture (USDA) has implemented several conservation programs to protect and improve natural resources and the environment associated with agricultural production. Although there are documented evidences on measuring the effects of conservation practices at the field-scale, information available on quantitative benefits of accumulation of the conservation practices at the national scale is very limited. Hence, the USDA has initiated the Conservation Effects Assessment Project (CEAP) which includes a modeling strategy to quantify the environmental benefits of conservation practices. Estimating the environmental benefits of conservation practices will allow policy-makers and program managers to evaluate the benefits of the existing programs and to design new programs more effectively and efficiently to meet the goals of the government (Mausbach and Dedrick, 2004).

Modeling is a feasible approach for assessing the effects of conservation practices on water quality benefits as establishing monitoring program for this purpose is cost prohibitive. Conservation practices are implemented on varying climate, soils and land management conditions across the nation. A modeling approach allows for considering these (spatial and temporal) variations and quantifying the effects of conservation practices across different agricultural regions. This paper describes the modeling approach used for evaluating the water quality benefits of conservation practices at the national scale in the CEAP.

Methodology

HUMUS/SWAT Modeling Approach for CEAP

The Hydrologic Unit Modeling for the United States (HUMUS) system a national-scale modeling framework developed to address several agricultural management related issues and other water quality and quantity management issues. HUMUS was developed as part of the Resources Conservation Act Assessment (RCA) of 1997. The United States Department of Agriculture- Natural Resources Conservation Service (USDA-NRCS), United States Department of Agriculture-Agricultural Research Service (USDA-ARS) and the Texas Agricultural Experiment Station (TAES) of Texas A&M University were the cooperators in this effort. The HUMUS system consists of (a) a basin scale hydrologic model, Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) to assess water quantity and water quality issues, and (b) a database to represent the spatial and temporal data required for SWAT (Srinivasan et al., 1998).

The HUMUS system follows the hydrologic unit accounting system of the United States. Figure 1 shows the 18 major river basins or 2-digit watersheds within the Conterminous United Status. Each river basin is divided into several 8-digit watersheds or Hydrologic Unit Codes (HUCs). The 2,108 HUCs within the Conterminous United States will be the study area in the HUMUS approach (Figure 1). On average, the area of a HUC is about 4,000 square kilometers. Each river basin is treated as a watershed and each HUC is treated as a subwatershed within HUMUS/SWAT modeling structure. Each HUC consists of several soil-land use combinations or Hydrologic Response Units (HRUs). The HUMUS modeling approach is revised significantly during the CEAP national assessment study in order to assess the off-site water quality benefits of the conservation practices at the 8-digit watershed levels (Figures 2 and 3). For the CEAP national assessment modeling effort, the revised HUMUS modeling approach uses the existing HUMUS structure along with updated databases and a recent version of SWAT (SWAT 2003). Additionally, the APEX model (Agricultural Policy/Environmental EXtender) (Williams et al.,

2000) is used to simulate the conservation practices implemented on cultivated cropland while SWAT is used to simulate the non-cultivated land and simulate the in-stream routing.

Models

The CEAP national assessment is primarily focussed on cropland where most of the conservation practices are implemented. Hence, the CEAP national assessment modeling approach uses two models: (i) the farm-scale model, APEX, to simulate the various conservation practices implemented in cultivated cropland and estimate the on-site impacts of the conservation measures, and (ii) the watershed scale model, SWAT, to assess the off-site water quality benefits of the conservation practices at the 8-digit watersheds. In the CEAP national assessment study, the APEX output for the cultivated cropland will be input into SWAT to assess the off-site water quality benefits of these conservation practices. SWAT will simulate the non-cultivated land and route the pollutants from non-cultivated land and point sources along with the APEX pollutant outputs for cultivated land to the outlet of each 8-digit watershed and then to the river basin outlet (Figure 2). The advantages of using APEX with SWAT for national assessment are that (a) it allows for simulation of cultivated lands with conservation practices to proceed independently and simultaneously with the watershed simulation and (b) allows for detailed simulation of cultivated lands than what is computationally feasible within a SWAT simulation.

The APEX model: APEX is a farm-scale physical process model and operates on a daily time step. APEX was developed by extending the capabilities of the field-scale model, EPIC (Environmental Productivity Impact Calculator) (Williams et al., 1984). The APEX model was constructed to evaluate various land management strategies considering sustainability, erosion (wind, sheet, and channel), economics, water supply and quality, soil quality, plant competition, weather, and pests. It has capability to simulate several agricultural management practices and conservation practices in detail. APEX has capabilities to simulate irrigation, drainage, furrow diking, buffer strips, terraces, waterways, fertilizer and manure management, lagoons, reservoirs, crop rotation and selection, pesticide application, grazing, and tillage (Williams et al., 2000). APEX simulates agricultural management processes on multiple fields and fate and transport of nitrogen, phosphorous, eroded soil and pesticides. Gassman et al. (2004) has provided the summary of the APEX development and applications.

The SWAT model: SWAT is developed to evaluate the impacts of different management conditions (point and nonpoint sources) on water quality in large un-gauged basins (Arnold et al., 1998; Neitsch et al., 2002; http://www.brc.tamus.edu/swat). SWAT is available within Environmental Protection Agency's modeling frame work called Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) (Di Luzio et al., 2002). It is a physically based simulation model, developed to simulate continuous–time landscape processes and streamflow with a high level of spatial detail by allowing the river/watershed to be divided into sub-basins. Each sub-basin is divided into several land use and soil combinations called hydrologic response units (HRUs). The model operates on a daily time step. Major components of the model include hydrology, weather, erosion, soil temperature, crop growth, nutrients, pesticides, and agricultural management. Several federal and state agencies and other research institutions have applied SWAT extensively from watershed scale studies to national scale studies. Arnold et al. (1999) and Borah and Bera (2004) have reported the applications of SWAT for various studies across the United States. SWAT has been applied for numerous other hydrologic and/or nonpoint source pollution studies (http://www.brc.tamus.edu/swat/swat-peer-reviewed.pdf).

Databases

APEX: For the CEAP national assessment, the APEX data sets are built around the National Resource Inventory (NRI). The NRI is a scientifically-based survey designed to assess conditions and trends of soil, water, and related resources of the Nation's non-federal lands at the national and regional level using a stratified two-stage unequal-probability area sample (Nusser and Goebel, 1997;USDA- NRCS, 2000). At each sample point, information is collected on nearly 200 attributes including land use and cover, soil type, cropping history, conservation practices, erosion potential, water and wind erosion estimates, wetlands, vegetative cover conditions, and irrigation method. These data will be used to develop APEX model inputs describing physical and environmental characteristics. For CEAP national assessment, farmer surveys are being conducted on a subset of National Resource Inventory sample points (30,000) to obtain information on current farming activities and conservation practices representing 2003-2006. This survey information will be used as site-specific management inputs for APEX. The APEX simulation outputs will be input into SWAT for analyzing scenarios on effects of conservation practices on water quality (USDA-NRCS, USDA-ARS and TAES, 2004).

SWAT: The HUMUS/SWAT system requires several databases such as land use, soils, management practices and weather. For the CEAP national assessment modeling effort, recently available data are processed to update the HUMUS/SWAT databases and prepare the SWAT input files for the 18 river basins (Figure 3).

Land use: The 1992 United States Geological Survey (USGS) -National Land Cover Data (NLCD) is the spatial data currently available for land use at 30-m resolution for the entire country (Vogelmann et al., 2001). For the CEAP assessment, the 1992 USGS land cover data set will be used as the base, which includes agriculture, urban, pasture, range, forest, wetland, barren and water. For the calibration simulations, 1992 land use data is used. For the CEAP baseline and alternative scenarios, 1997 land use conditions will be used. The 1992 USGS land cover data set is adjusted to represent 1997 land use conditions by using the relative changes in land use as determined by the 1992 and 1997 NRI data (Nusser and Goebel, 1997; USDA-NRCS, 2000).

Soils: Each land use within an 8-digit watershed is associated with soil data. Soil data required for SWAT were processed from the STATe Soil GeOgraphic (STATSGO) database (USDA-NRCS, 1994). Each STATSGO polygon contains multiple soil series and the aerial percentage of each. The soil series with the largest area was extracted and associated physical properties of the soil series were extracted for SWAT.

Topography: Topographic information on accumulated drainage area, overland field slope, overland field length, channel dimensions, channel slope, and channel length derived from the DEM data in the previous HUMUS project (Srinivasan et al., 1998) will be used in this modeling effort.

Management Data: Management data is important in the SWAT model. Management operations such as planting, harvesting, applications of fertilizers, manure and pesticides and irrigation water and tillage operations along with timings or potential heat units are to be specified for various land uses in the management files. Management operations/inputs vary across regions. These data are being gathered for land uses such as horticulture, pasture and hay that are simulated in SWAT from various sources such as Agricultural Census Data and USDA-National Agricultural Statistics Service (NASS)'s agricultural chemical use data.

Weather: Measured daily precipitation and maximum and minimum temperature data sets from 1960 to 2001 are used in this modeling approach. The precipitation and temperature data sets are created from a combination of point measurements of daily precipitation and temperature (maximum and minimum) (Eischeid et al., 2000) and PRISM (Parameter-elevation Regressions on Independent Slopes Model) (Daly et al., 1994; Daly et al., 2002). The point measurements compose a serially complete (without missing values) data set processed from the NCDC (National Climatic Data Center) station records. PRISM is an analytical model that uses point data and a digital elevation model (DEM) to generate gridded estimates of monthly climatic parameters. PRISM data are distributed at a resolution of approximately 4 km^2. A novel approach has been developed to combine the point measurements and the monthly PRSIM grids to develop the distribution of the daily records with orographic adjustments over each USGS 8-digit watersheds (M. Di Luzio, personal communication, 20 March 2005). Other data such as solar radiation, wind speed and relative humidity will be simulated using the weather generator (Nicks, 1974; Sharpley and Williams, 1990) available within SWAT.

Point Source Data: Effluents discharged from the municipal treatment plants are major sources of point sources. The USGS has developed a point source database for use in the 1992 SPARROW simulations and it will be used in the calibration runs. Point sources for a year near 1997 will be estimated using human population and it is assumed that these estimates are valid for 3-5 years before and after the year they were developed.

Atmospheric Nitrogen Deposition: Atmospheric deposition can be a significant component of nitrogen balance and contribute to plant growth and nitrogen runoff concentrations especially in some of non-agricultural land. Hence, estimates of nitrogen deposition (nitrate and ammonium) are incorporated into SWAT and APEX models. Nitrogen deposition data set (loads and concentration) is developed from the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) database (NADP/NTN, 2004) which consists of yearly deposition grids available for the entire nation. These data are processed for creating nitrogen deposition records for each 8-digit watersheds (M. Di Luzio, personal communication, 10 April 2005). Atmospheric deposition data is available from 1994 to 2001.

Model Calibration and Validation

APEX and SWAT models are built with an attempt to simulate the processes physically and realistically as possible. Although most of the model inputs are physically based and can be obtained from existing landscape properties and management conditions, there is still some uncertainty in inputs. Hence, there is a need for model calibration.

APEX: The initial focus of the calibration efforts for APEX model will involve yield and soil erosion. Calibration efforts will then be extended to nutrients, carbon, and pesticides as data availability allow.

SWAT: There is not adequate water quality monitoring data available for SWAT model calibration at each 8-digit watershed. The United States Geological Survey (USGS) has developed a regression model called SPARROW (SPAtially Referenced Regressions On Watershed attributes) to simulate the flow and nutrients for the entire nation (Smith et al., 1997). SPARROW uses regression equations that relate measured transport rates in streams to spatially referenced descriptors of pollution sources and land-surface and stream-channel characteristics. SPARROW estimates (a) runoff, sediment and nutrient loadings within each 8-digit and (b) streamflow, sediment and nutrients leaving the outlet of each 8-digit watershed. As the SPARROW estimates are based on 1992 land use, the HUMUS calibration will be performed using 1992 land use data. HUMUS/SWAT simulated loadings will be calibrated using average annual flow and loads for each 8-digit watershed predicted by SPARROW. In addition, calibration of daily concentration distributions (i.e., 25, 50, 75 and 90 percentiles) at a few selected gages within each of the 18 major river basins will be performed (Figure 3). This will give confidence in the SWAT estimates on the number of days the pollutant concentrations exceeding human health and ecological thresholds.

Additional water quality data from a few USGS gages (not used in calibration) at major locations in the 18 river basins will be used for model validation. The models will be run without any adjustment to input parameters. Model validation is critical for ensuring scientific support of the modeling approach.

For calibration and validation runs, SWAT model will use APEX outputs for cultivated cropland obtained using the National Nutrient Loss and Soil Quality Database (NNL&SQ Database) (Potter et al., 2005). SWAT uses the 1992 land use conditions for the calibration.

Scenario Analysis

The calibrated HUMUS/SWAT model will be used to develop various scenarios to assess the effects of conservation practices on off-site water quality benefits (Figure 3). HUMUS/SWAT modeling inputs remain the same for all scenarios except for the variations in APEX outputs input into SWAT. SWAT will use the 1997 land use conditions for these scenarios.

CEAP Baseline Scenario: HUMUS/SWAT simulation will be made using the APEX output generated for cultivated cropland with conservation practices currently in use based on the farmer survey.

Alternative Scenario: HUMUS/SWAT simulation will be made using the APEX output generated for cultivated cropland using farmer survey records assuming no conservation practices were applied.

The off-site water quality benefits of conservation practices currently in use will be determined by comparing model outputs for the alternative scenario to those of the CEAP Baseline at each 8-digit watershed. Benefits will be reported as (a) reductions in in-stream concentrations and loadings of sediment, nutrients and pesticides, and (b) reductions in the number of days that concentrations of nutrients or pesticides exceed human health and ecological thresholds.

Conclusion

Information regarding the quantitative benefits of conservation practices or programs on water quality is imperative to improve the existing conservation programs and develop new programs and for efficient utilization of the resources. Modeling is a potential option for evaluating the effects of conservation practices on water quality benefits. This paper described the modeling approach used for estimating the water quality benefits of conservation practices at the national level in the CEAP. The modeling approach is useful to analyze several scenarios that might be helpful for policy makers and conservation managers in planning the conservation programs or practices.

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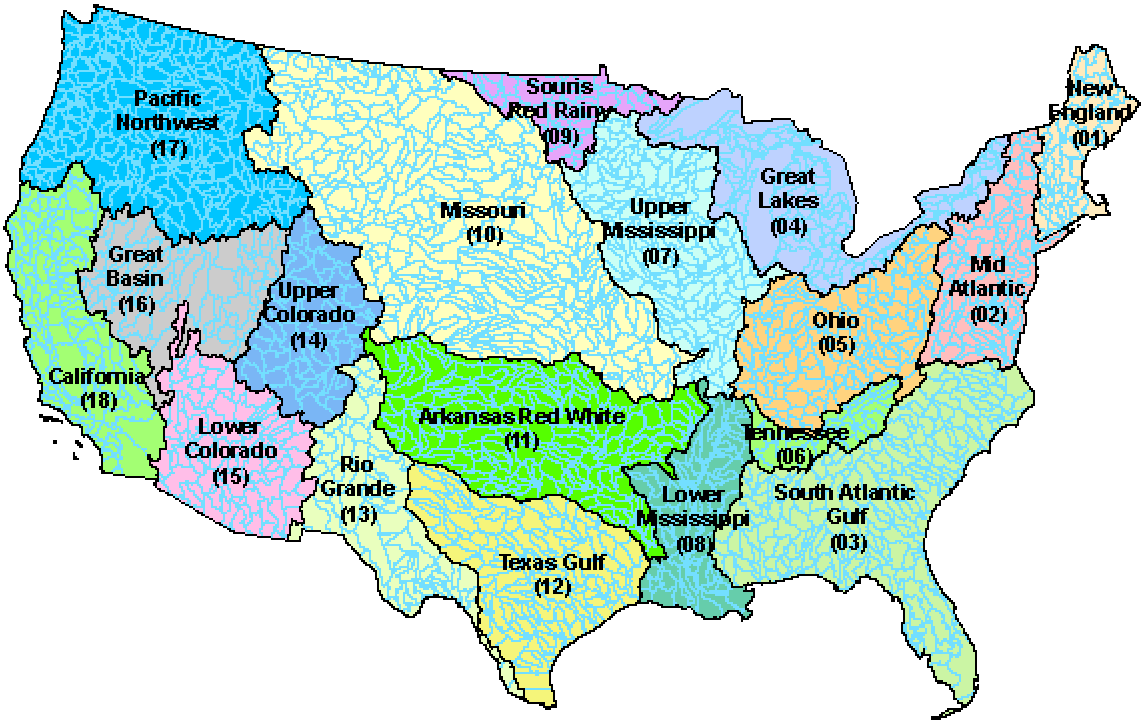

Figure 1. Major river basins and 8-digit watersheds (HUCs) in the Conterminous United States

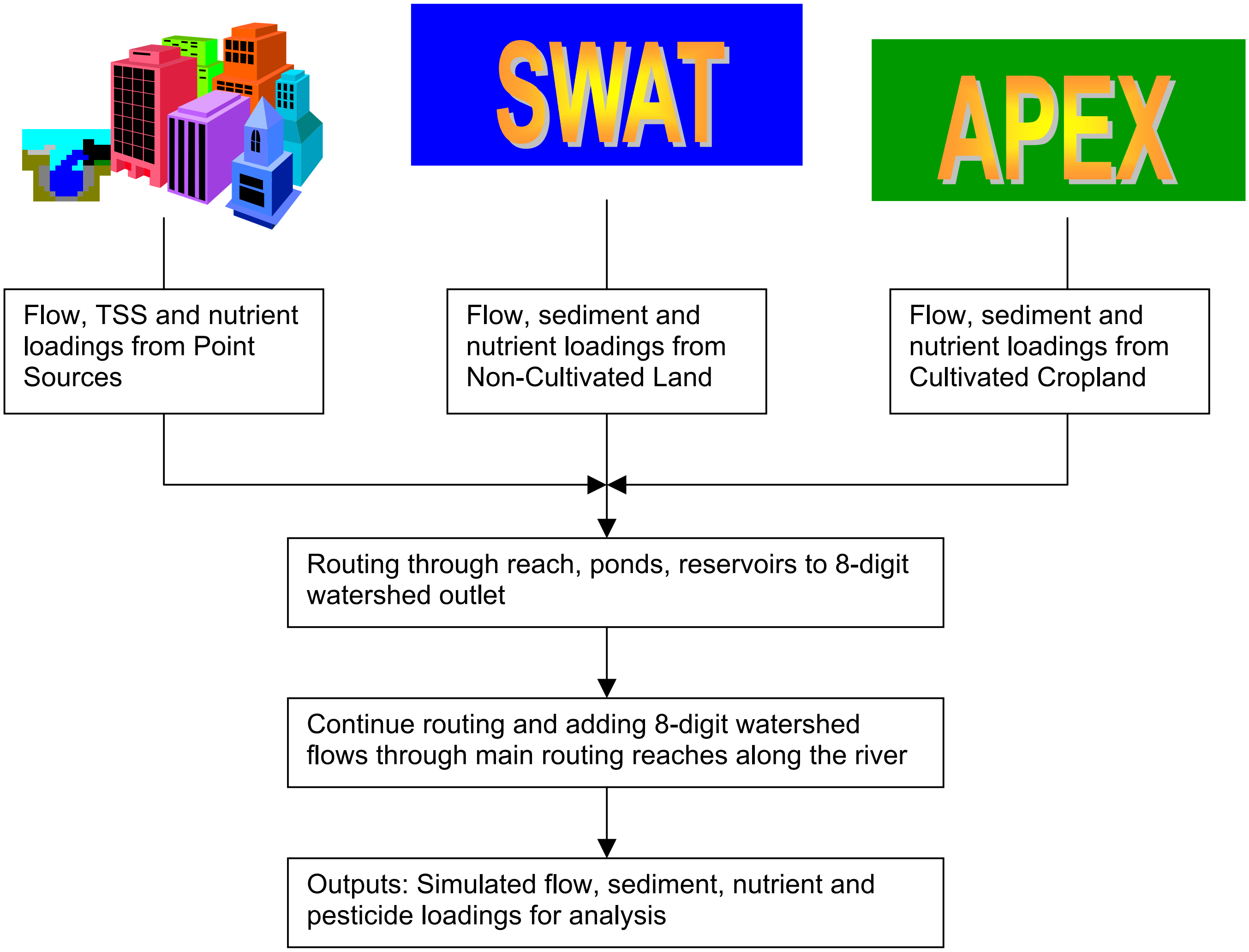

Figure 2. HUMUS/SWAT modeling processes for CEAP national assessment

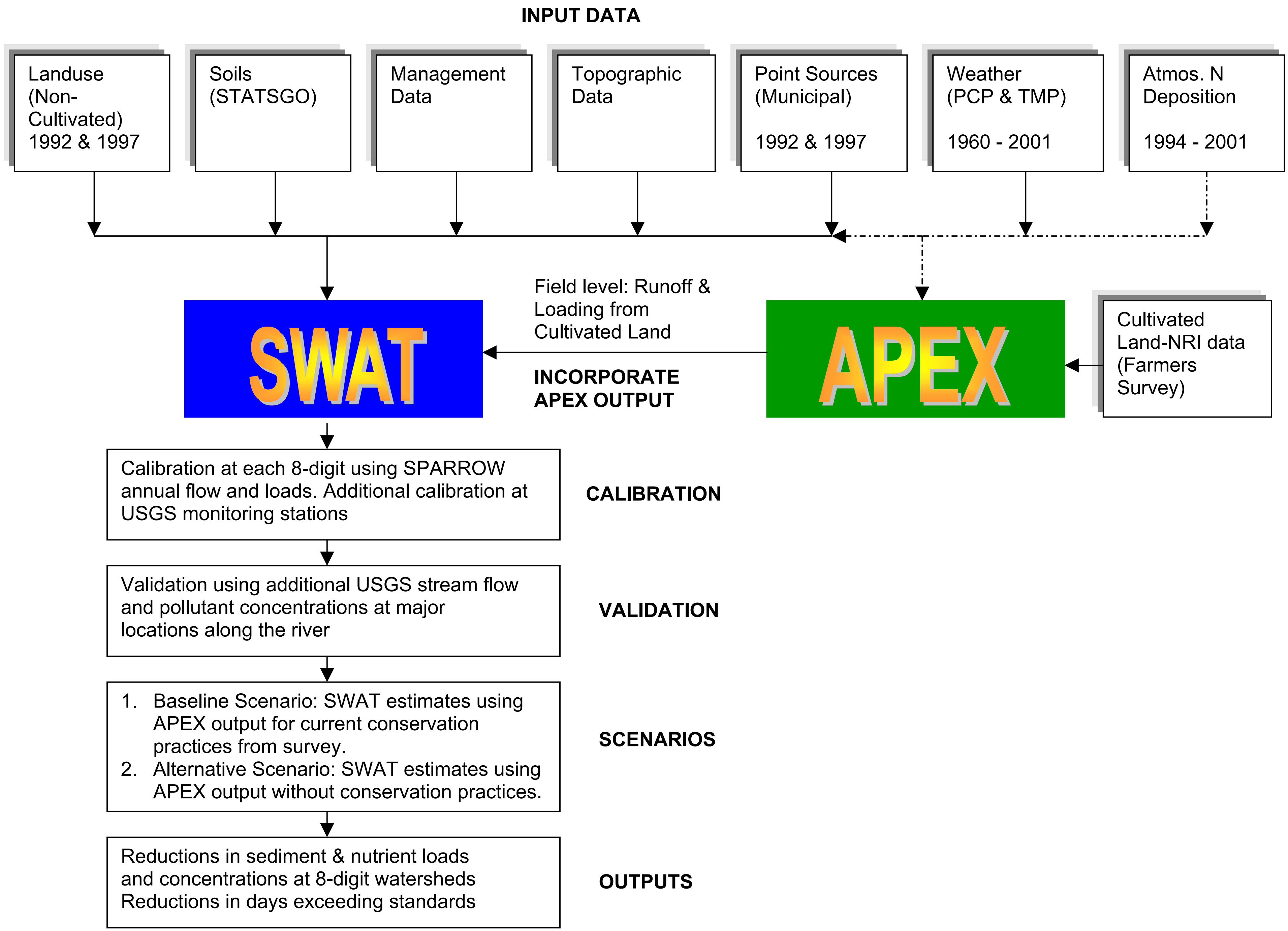

Figure 3. HUMUS/SWAT modeling approach for CEAP national assessment