Modeling Tools for Watershed Planning

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What do you think of when you hear the word model?
An introduction to modeling the landscape
What Kind of Models Are There?

- Physical Models
  - scale models and dynamic similitude
What Kinds of Models Are There?

- Maps and Digital Displays
  - topographic, soils, land use
What Kinds of Models Are There?

- Mathematical Models for Hydrology
  - “a collection of physical laws and empirical observations written in mathematical terms and combined in such a way as to produce hydrologic estimates (outputs) based on a set of known and/or assumed conditions (inputs)”
Why Use Watershed Models?

• Models provide an understanding of a watershed and its response to change that is difficult to obtain any other way

• COST - Monitoring is resource intensive

• Is it not possible to monitor something that has not yet occurred

• Monitoring every field or plot is just is not feasible at the watershed scale
Potential Uses:

- Assess sources of pollutant loadings from non point, point, and channel sources within a watershed at various temporal scales.

- Develop TMDLs.

- Develop plans for watershed protection and remediation.

- Identify critical areas or “hot spots” that contribute substantially to pollutant loads.

- Compare the impact of an array of best management practices on reducing pollutant loadings from the landscape or stream systems.

- Evaluate the impact of seasonal or decadal scale climatic variations on water quantity and water quality.
Applicable Model Scales and Types

Field Scale: USLE, EPIC, GLEAMS, WEPP

Farm Scale: AGNPS, APEX

Watershed Scale: GWLF, SWAT, WARMF, HSPF

In-stream and Lake/Reservoir: QUAL-2E and 2K, BATHTUB, CE-QUAL-W2
Level of Sophistication of Watershed-Scale Models

- **Parametric**—represents hydrologic processes by means of algebraic equations that contain key parameters to be determined empirically.

- **Conceptual**—a simplified representation of the physical processes, obtained by lumping spatial or temporal variations, and described in terms of either ordinary differential equations or algebraic equations.

- **Deterministic**—formulated by using laws of physical, chemical, or biological processes as described by partial differential equations.
Pollutant Transport Models

- USLE
- GWLF
- STEPL
- RUSLE2
- WEPP
- ANSWERS
- EUTROMOD
- AGNPS
- PLOAD
- EPIC
- CE QUAL W2
- BATHTUB
- QUAL2E/2K
- WASP
- SWMM
- STORM
- AQUATOX
- CREAMS
- GLEAMS
- PRZM
- SWAT
- SPARROW
- WARMF
- HSPF
- APEX
Selected Models by Scale

- Field Scale Models
  - USLE and RUSLE
  - WEPP
  - GLEAMS
- Farm / Small Watershed Scale Models
  - AnnAGNPS
  - APEX
- Watershed Scale Models
  - STEPL
  - GWLF
  - SPARROW
  - WARMF
  - SWAT
GIS input datasets interface with models

- **Climate**
  - Precipitation & Temp
  - Recording gages

- **SOILS**
  - Statsgo or Surgo

- **LANDUSE**
  - Landsat –5
  - Thematic Mapper image

- **DEM**
  - USGS digital elevation model
USLE = Universal Soil Loss Equation

- USLE initially developed as a tool to assist soil conservationists in farm planning
- Used to estimate soil loss on specific slopes in specific fields
- Based on rainfall, soil, topographic, and land management practices
Revised USLE

- update is based on an extensive review of the USLE and its data base, analysis of data not previously included in the USLE, and theory describing fundamental hydrologic and erosion processes
- Computerized algorithms to assist with calculations
- New or improved approaches for estimating R, K, C, LS, and P factors
- Often embedded in farm, field, or watershed scale models
Water Erosion Prediction Project = WEPP

- Developed by the USDA ARS to predict erosion on hillslopes and small watersheds
- Continuous simulation, process-based model
- Based on physical descriptions of rill and interrill erosion processes and sediment transport mechanics
- (Does not use principles or logic from the USLE)
- Performs simulations on a daily time step
- Applicable for small watersheds up to 1 sq mile
WEPP considers 8 major components:

- Climate
- Infiltration
- Water Balance
- Plant Growth and Residue Decomposition
- Tillage and Consolidation
- Surface Runoff
- Erosion
- Winter Processes
WEPP Components:

• Windows-based user interfaces allowing for data entry, management, and displays of results

• Integration of GIS technology for information on elevation, slope, soils, climate (GEOWEPP)

• Detailed BMP options for agriculture, range, and forested areas
Ground Water Loading Effects of Agricultural Management System Model = GLEAMS

• used to simulate water quality events on an agricultural field
• evaluates the hydrologic and water quality response of many different scenarios:
  -- various types of tillage and cropping systems
  -- wetland conditions
  -- subsurface drained fields
  -- agricultural and municipal waste application
  -- nutrient and pesticide applications
GLEAMS

- Built upon the strength of its predecessor, CREAMS developed by USDA ARS
- Considers tillage, crop, fertilizer, and livestock practices
- A continuous simulation, landscape and root zone model that provides detailed prediction of:
  -- water
  -- sediment
  -- nutrients
  -- pesticides
GLEAMS Hydrology and Erosion

- Hydrologic computations for evapotranspiration, percolation, infiltration, and runoff are determined using a daily time step.
- employs SCS curve number method
- continuity of mass to predict erosion (USLE) and sediment transport (modified Yalin Eq.) under different topographic and cultural conditions.
Soil Organic Matter

- Symbiotic fixation
- Mineralization
- Immobilization
- Nitrification
- Anaerobic conditions
- Denitrification
- Leaching
- Nitrification

Nitrogen Cycle

- Harvest
- NH₃
- Runoff
- Ammonia volatilization
- Fertilizer
- Manures, wastes

Fertilizer

N₂, N₂O

N₂O
Soil Organic Matter

$\mathrm{H}_2\mathrm{PO}_4^-$

$\mathrm{HPO}_4^{2-}$

mineralization

immobilization

Adsorbed and fixed Inorganic Fe, Al, Ca, and clay

fertilizer

manures, wastes, and sludge

runoff

Harvest

manures, wastes and sludge

Soil Organic Matter
GLEAMS Model Strengths

• Comprehensive simulation of processes related to the movement of water and pollutant constituents in agricultural settings

• Very detailed N, P, and Pesticide algorithms that have been incorporated into other USDA ARS watershed models

• Simulates up to 10 types of pesticides
Selected Models by Scale

- Farm/ Small Watershed Scale Models
  - AnnAGNPS
  - APEX
Annualized Agricultural Non-Point Source Pollution Model = AnnAGNPS

- a spatially distributed, comprehensive, continuous simulation model
- developed by extensively revising and upgrading the AGNPS storm event model
- simulates surface runoff, soil erosion, and transport of sediment, nutrients, and pesticides
- also simulates snowmelt, irrigation, subsurface flow, tile drain flow, feedlots, and gullies at continuous daily or sub-daily time steps
- divides the watershed into homogeneous drainage areas, which are then integrated together by simulated rivers and streams, routing the runoff and pollutants from each area downstream
AnnAGNPS: source accounting

- **cell A**
- **cell B**
- **cell C**
- **cell D**
- **cell E**
- **cell F**

- **reach 1** from feedlot to **cell A**
- **reach 2** from **cell B** to **cell D**
- **reach 3** from **cell C** to **cell F**
- **reach 4** from **cell E**

- 10% of outlet sediment from gully
- 80% of outlet pest X from cell C
- 25% of outlet nitrogen from feedlot

**watershed outlet**
Landscape Erosion

Rill and Intermill Erosion
computed by RUSLE

Sediment Delivery
computed by Hydro-geomorphic USLE (HUSLE)
utilizes surface runoff volume and peak discharge to compute sediment yield
considers sediment yield particle-size distribution for five particle classes

Ephemeral Gully Module
calculates the mass of sediment and sediment-attached nitrogen, phosphorus, and organic carbon added to the stream system for a given storm event from a given gully in the watershed

mass of sediment and attached nutrients vary in proportion to the amount of runoff flowing through the gully based upon user-supplied equation constants
Model Strengths

• Output re-formatting and analysis functions
• Excellent crop and livestock management operations
• Robust simulations of sediment, nutrients, and pesticides
• Ephemeral gully erosion component
• Integrated with CONCEPTS stream corridor model
• Integrated with SNTEMP in-stream temperature model
Model Limitations

- Considerable time commitment for developing input files to describe management field operations
- Lacks ground water flow component
- Intermediate subject knowledge and technical difficulty level
APEX

AGRICULTURAL POLICY / ENVIRONMENTAL EXTENDER MODEL

• Whole farm/watershed scale
• Subarea component (EPIC)
• Routing (water, sediment, nutrients, pesticides)
• Groundwater & reservoir components
• Capable of simulating 100’s of years
• Daily time step
• Development began in 2000
The EPIC MODEL

• Weather
• Hydrology
• Erosion (wind & water)
• Carbon
• Nutrients (N, P, & K)
• Pesticides

• Salinity
• Crop Growth
• Tillage
• Grazing
• Manure Management
• Economics
• Nitrogen
  - Surface runoff
    ▪ soluble and adsorbed
  - Subsurface flow
    ▪ lateral and vertical

• Phosphorus
  - Surface runoff
    ▪ soluble and adsorbed
PESTICIDE FATE GLEAMS

- Surface runoff
  - soluble and adsorbed

- Leaching

- Degradation
  - from foliage and soil

- Washoff from plants
  - rainfall or irrigation
APEX

• Management capabilities
  – Irrigation
  – Drainage
  – Furrow diking
  – Buffer strips
  – Terracing
  – Waterways
  – Fertilization
  – Manure management
  – Wetlands
  – Reservoirs
  – Crop rotation and selection
  – Pesticide application
  – Grazing
  – Tillage
APEX model strengths

- Comprehensive hydrologic, water quality, crop growth algorithms
- very detailed agricultural management functions--well suited for watersheds characterized by crops and livestock
- well proven for smaller watersheds
- readily available link to SWAT
- outstanding BMP representation
Selected Models by Scale

• Watershed Scale Models
  – STEPL
  – GWLF
  – SPARROW
  – WARMF
  – SWAT
Spreadsheet Tool for Estimating Pollutant Load = STEPL

- developed for U.S. Environmental Protection Agency (USEPA) by Tetra Tech, Inc.
- employs simple algorithms to calculate nutrient and sediment loads from different land uses
- estimates load reductions resulting from the implementation of various best management practices (BMPs)
- computes
  -- surface runoff
  -- nitrogen
  -- phosphorus
  -- 5-day biological oxygen demand (BOD5)
  -- sediment delivery (USLE and delivery ratio)
Spreadsheet Tool for Estimating Pollutant Load = STEPL

• Uses Visual Basic (VB) interface to generate a spreadsheet in EXCEL
• VB interface allows users to customize the generated spreadsheet in terms of the number of subwatersheds to include in the project
• For each subwatershed, the annual nutrient loading is calculated based on:
  --runoff volume
  --pollutant concentrations in the runoff water
  --land-use distribution and management practices
STEPL Pollutant Sources

- Cropland
- Pastureland
- Farm animals
- Feedlots
- Urban runoff
- Septic systems (including failure rates)
- Gully and streambank erosion
STEPL Output

• assesses the relative significance of different pollutant sources
• generates gross estimates of pollutant loadings
• typically applied on a subwatershed basis, where loading can be aggregated over longer time frames
• provides a rapid means of identifying different pollutant sources
• simulates the impact of various types and arrangements of BMPs on an annual basis with minimal effort and data requirements
• suitable for conducting preliminary planning level investigations
Generalized Watershed Loading Functions = GWLF

- developed at Cornell University as “a compromise between the empiricism of export coefficients and the complexity of chemical simulation models”
Model Assumptions: combined distributed/lumped parameter watershed model

- Watershed is divided into surface, unsaturated, and saturated zones.
- Distributed approach for surface loading in the sense that it allows multiple land use/cover scenarios (each assumed to be homogenous).
- Does not spatially distribute the source areas.
- Lumped parameter model for sub-surface loading.
Sediment Loading Function

- erosion estimated using monthly erosion calculations based on the USLE algorithm (with monthly rainfall-runoff coefficients) and a monthly composite of KLSCP values for each source area

- sediment delivery ratio based on watershed size and a transport capacity based on average daily runoff
Nutrient Losses

• rural surface nutrients estimated from empirical N and P concentrations of each land use, based on both dissolved concentration in runoff and solid concentration in sediment

• sub-surface losses calculated using dissolved N and P coefficients for shallow groundwater contributions to stream nutrient loads from a single, lumped-parameter sub-surface contributing area
Miscellaneous nutrient sources

- Point source discharges contribute to dissolved losses and are specified in terms of kilograms per month
- Simulates effluent from on-site septic systems
- Urban nutrient inputs are assumed to be solid-phase, with an exponential accumulation and washoff function used for these loadings
Additional Model Components

- monthly streambank erosion based on a watershed specific lateral erosion rate and channel properties and dimensions
- monthly surface water and groundwater withdrawals
- direct simulation of loads from farm animals
- pathogen load estimation routine
- considers best management practices (BMPs) and other mitigation activities on pollutant loads
• Provides linkage to GWLF watershed model via use of ArcView GIS Interface
• Automatically creates input files for revised version of GWLF
• Provides ability to consider pollution mitigation activities, such as BMPs
GWLF Model Strengths

- a relatively simple model
- requires a low level of modeling expertise
- can be quickly applied to evaluate potential loadings with some recognition of seasonal variability
GWLF Model Limitations

• Simplifications in stream transport and water quality simulation (e.g., constant constituent concentrations)

• Highly simplified flow routing and groundwater inflow representation

• Stormwater storage and treatment are not considered

• Low level of technical support
Spatially Referenced Regression on Watersheds = SPARROW

• Relatively new tool developed by the USGS
• Based on compilation of regional water quality data
• Uses nonlinear regression techniques to calibrate simple, structural models of riverine water quality
• In-stream water quality measurements related to spatially referenced characteristics of watersheds, including pollutant sources and land-surface characteristics that affect pollutant delivery
SPARROW

- Used to simulate nitrogen, phosphorus, suspended sediment, and fecal coliform loadings
- Ideal for large rivers where other types of modeling are difficult or expensive
- Simulations provide a good "first look" at major source contribution areas
Location of 1,828 water-quality monitoring stations used in the SPARROW sediment model

The model identified six sources of sediment:

--stream channel
--urban
--forested
--nonforested
--agricultural
--other
What does SWAT stand for?

- What kids used to get when they messed up big time
- Special Weapons and Attack Team
- Students Working Against Tobacco
- A troubled valley in Northern Pakistan
- Soil and Water Assessment Tool
Schematic Diagram of SWAT Development History

- **CREAMS** → Daily Hydrology Component
- **GLEAMS** → Pesticide Component
- **EPIC** → Crop Growth Component
- **SWRRB** → Routing Structure
- **QUAL2E** → In-stream Kinetics
- **SWAT**
HRU’s
28% Range-Sandy
51% Pasture – Silt
16% Forest – Sandy
4% - Agriculture - Silt
Upland Processes

- Weather
- Hydrology
- Sedimentation
- Plant Growth
- Nutrient Cycling
- Pesticide Dynamics
- Soil Temperature
- Management
- Bacteria
Evaporation and Transpiration

Precipitation

Infiltration/plant uptake/ Soil moisture redistribution

Surface Runoff

Lateral Flow

Return Flow

Revap from shallow aquifer

Percolation to shallow aquifer

Recharge to deep aquifer

Flow out of watershed

Hydrologic Balance
Development of a biozone layer as a result of on-site waste water septic tank effluent.

Waste water source

Pretreatment

Effluent delivery

Biozone created by build up of bacteria, which enhances:
- sorption
- nitrification
- biological decay
- bacterial die-off

Biozone

Vadose zone

Infiltration

Percolation

GW Recharge

Ground water zone
In stream water quality processes simulated in SWAT
In-stream Nutrient Processes

Well-mixed Water Layer

Transport in:
- Org N
- NH₄
- NO₂
- NO₃

Transport out:
- Dissolved Oxygen
- Carbonaceous BOD
- Org P
- Dissolved P
- Chlorophyll a
- Algae

Sediment Layer

Benthic Demand for Oxygen

Benthic Sink/Source for Nutrients
SWAT Strengths

Comprehensive Hydrologic Balance
Physically-Based Inputs
Plant Growth – Rotations, Crop Yields
Nutrient Cycling in Soil
Land Management – BMP
  Tillage, Irrigation, Fertilizer, Pesticides,
  Grazing, Rotations, Subsurface Drainage,
  Urban-Lawn Chemicals, Street Sweeping
Hormone fate and transport algorithm under development
SWAT Strengths

Flexible Watershed Configuration
Water Transfer—Irrigation Diversions
Sediment Deposition/Scour
Organic N and P detachment by bank erosion
Pond and Wetland Impacts
Improved Bacteria fate and transport algorithm under development
SWAT Strengths

Model Calibration
  Parameter Sensitivity Analysis
  Autocalibration Tool
  Parameter Uncertainty Analysis
  Model Uncertainty Analysis

Very Good User Support
SWAT Limitations

- Lacks the capability of modeling cation and anion fate and transport
- Simplistic metals simulation
- Considerable effort required for estimating pollutant source loads from various land cover types (post processing)
- Simplistic approach to impoundment simulation
- Computations at sub-daily time step require use of Green-Ampt Infiltration option
What is WARMF?

Watershed Analysis Risk Management Framework

- Developed by Systech Engineering, Inc.
- GIS based watershed model and Decision Support System
- Physically based, dynamic model
- Friendly tool, easily transferred to stakeholders
- Well-suited for answering questions during the TMDL process
WARMF MODULES

WATERSHED APPROACH

IMDL
Consensus
Data
Knowledge
Function of Modules:

- Consensus Module
  --supplies scientific information to stakeholders for alternative evaluations that affect water quality
  --allows stakeholders to consider all water quality issues for the entire basin (point and nonpoint source pollution)
  --engages local stakeholders in the decision making process, so that they can consider local conditions and all cost effective measures including pollution trading
Unique Features:

- simulates nutrient and bacteria losses from on-site septic systems
- simulates water quality fate and transport in lakes/reservoirs; includes link to the 2 Dimensional CE-QUAL-W2 Model
- simulates metals such as iron, zinc, manganese, copper, and mercury
- readily displays measured versus simulated water quality constituents
Hydrologic and Pollutant Simulation:

- Streamflow
- Temperature
- Sediment
- Nutrient constituents
- BOD
- Pathogens
- Constituent suspended sediment
- Pesticides
- Phytoplankton and Periphyton
- Metals (Al, Fe, Zn, Mn, Cu, Hg from acid mine drainage)
- Common cations and anions
Watershed Configuration

WARMF divides a river basin into land catchments, river segments, and stacked reservoir layers.
Landscape Processes:

- Atmospheric Deposition
- Canopy Reactions—SOx and NOx
- Snowpack Chemistry—ion leaching
- Leaf Litter—accumulation and decay
- Soil Temperature—heat budget eq. for each layer
- Nutrient Uptake by Plants
- Root Respiration (CO2 release to soil due to energy expended to extract water and nutrients from soil)
Landscape Processes:

- Anion Adsorption to soil—phosphate and sulfate
- Cation Exchange, Precipitation, and Complex Ion Formation
- Mineral Weathering and Acid Mine Drainage
- Nitrification and Denitrification
- On Site Septic Systems (3 Types—traditional, advanced, failing)
Strengths of WARMF

• Separate autocalibration of streamflow and water quality constituents
• Many physically based processes simulated
• Rural on-site septic system simulation
• Simulation of cations, metals, and acid mine drainage
• Graphical and statistical comparison of measured versus simulated results
• Displays spatial distributions of point and nonpoint loading using GIS map format
Strengths of WARMF

• Displays water quality status in terms of suitability for fish habitat, swimming, water supply, and other uses with red and green color codes

• Linked with CE-QUAL-W2 Reservoir Model with vertical and longitudinal profiles of water quality

• Rapid assessments of BMPs and specific management plans based on stakeholder’s decision making processes
Limitations of WARMF

• No display of water budget to evaluate calibration of hydrologic components such as surface runoff, lateral flow or ET
• Labor intensive for constructing complex watersheds
• Generalized crop characteristics
• Bottom soil layer does not adequately reflect shallow aquifer groundwater movement
• Moderate level of modeling expertise required
• Contact with SysTech Engineering may be necessary for technical support
Model Selection Considerations

- What questions will the model be used to address?
- Is the model designed to link management options to meaningful response variables?
- Have appropriate spatial and temporal modeling scales been selected for the problem at hand?
- Can a simple model be used instead of a complex one?
- Is it possible that no model may not be necessary at all (such as for low flow conditions)?
Model Selection Considerations

• How well does the model represent landscape and aquatic ecosystems?
• Is there some way that model prediction uncertainty can be evaluated?
• Is there consistency between model input requirements and the availability of data?
• Are model results credible to stakeholders? Can the modelers provide suitable explanations in describing model processes and predictions?
• Is the model flexible enough to allow updates and improvements?
Model Selection Considerations

- Will training be necessary to implement a particular model?
- Who will be responsible for developing the model project?
- What kind of time frame will be necessary for model construction, data input, calibration, scenario development, model update and maintenance?
- Is the cost for model support an acceptable long-term expense?
Scientists from the RAND Corporation have created this model to illustrate how a “home computer” could look like in the year 2004. However, the needed technology will not be economically feasible for the average home. Also, the scientists readily admit that the computer will require not yet invented technology to actually work, but 50 years from now scientific progress is expected to solve these problems. With teletype interface and the Fortran language, the computer will be easy to use.
QUAL2K

- A one dimensional, steady state model for stream and river channels
- Heat budget, temperature, and water quality constituents are simulated as a function of meteorology on a diurnal time scale
- Point and non-point loads and abstractions are simulated
In-stream and Lake/Reservoir Models

- QUAL 2E and QUAL 2K
- BATHTUB
- CE-QUAL-W2
BATHTUB

1 Dimensional model for rivers, lakes, reservoirs and river basin systems
Bathtub Lake/Reservoir Modeling System

• Steady state water quality model
• designed to relate eutrophication symptoms to external nutrient loadings, hydrology, and reservoir/lake morphometry
• based on statistical methods derived from a representative cross section of water bodies
• can be used to predict the effects of future changes in external nutrient loadings
CE-QUAL-W2

2 Dimensional model for rivers, lakes, reservoirs and river basin systems

\[ Q_{\text{in}} \]

\[ Q_{\text{out}} \]
CE-QUAL-W2

• two-dimensional, laterally averaged, finite difference hydrodynamic and water quality model
• assumes lateral homogeneity, therefore best suited for relatively long and narrow water bodies exhibiting longitudinal and vertical water quality gradients
• Ideal for stratified reservoirs that are highly influenced by seasonal circulation patterns
• tributaries that extend from the main reservoir can be modeled as separate branches
Output Parameters

- temperature
- organic carbon
- total dissolved solids
- coliform bacteria
- inorganic suspended sediments
- dissolved organic matter
- biochemical oxygen demand
- algae and detritus
- constituents of phosphorus and nitrogen
- dissolved oxygen
- iron
- alkalinity and pH
- bottom sediments
QUAL2K

- River reaches are subdivided into a number of segments
- Further subdivides segments into computational elements
- A physically based simulation model that obtains solutions by a numerical algorithm
QUAL2K

• Temperature
• pH
• DO and BOD
• Phytoplankton and Bottom Algae
• Constituents of N and P
• Coliform Bacteria
• Conservative and Non-conservative Constituents
BATHTUB Model Features

• nonlinear nutrient sedimentation kinetics
• algae growth limitation by phosphorous, nitrogen, light, and flushing rate
• predicts lake and reservoir responses to nutrient loadings on a yearly basis based or over the growing season
• inflow nutrient partitioning (bioavailability of dissolved versus particulate loadings)
• seasonal variations in loadings and morphometry
• spatial variations (longitudinal gradients) in nutrients and related trophic state indicators
Model Outputs

- nutrient and water balances in a segmented hydraulic network
- nutrient sedimentation
- algal (chlorophyll) response to flushing, light and nutrient concentration
- oxygen depletion
- in-lake total P (TP)
- ortho-P
- organic N
- Secchi depth (transparency)
CE-QUAL-W2

- Describes unsteady vertical and longitudinal distributions of water quality constituents in the water column and bed sediments in response to loadings from:
  - Upstream
  - Tributaries
  - Overland flow
  - Groundwater
  - Atmosphere
The model accommodates variable grid spacing (segment lengths and layer thicknesses) so that greater resolution in the grid can be specified where needed.