Basin-scale real-time flow and salt load model-based visualization tools for forecasting and TMDL compliance

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Abstract
A wealth of freely available real-time hydrologic and water quality data are provided by governmental organizations including in situ observations and geospatial data sets. Despite having access to this information, much of the data remain underutilized due in part to the time required to access, obtain, and integrate data from different sources. Although numerical simulation models have become strongly associated with visualization of information for decision support – we often overlook data visualization as a quicker and easier way to make some management decisions. Data visualization often needs to go beyond mere rendering of sensor data at a single monitoring site – it often involves combining flow and water quality sensor data to provided information on pollutant loading or, in the case a salinity management, daily assessment of ability to meet salt load targets. Both data and model output visualization tools can be used by water resource managers to understand how salt loads might be managed from multiple sources to achieve Basin-scale real-time salinity management. This white paper reviews a number of model-based water quality simulation models that can serve as visualization tools as well as two recent examples of data visualization applied to salt management in the San Joaquin Basin. The paper also suggests simulation models and visualization tools that might be capable of replacing the WARMF-SJR model, the most popular model in current use by Reclamation and other State agencies to simulate salt management actions and forecast future flow and salinity conditions in the San Joaquin River. Also to suggest future enhancements in the WARMF-SJR model remains the model of choice or the development of a next generation water quality model for the San Joaquin River Basin.

1. Introduction

Simulation and forecasting have become integral for optimal water quantity and quality management in river basins, worldwide. However the suite of tools available to perform these complex management functions have not kept pace with advances in database, real-time data processing, GIS, sensor and remote sensing technologies. Many of the river basin simulation models in everyday use are based on 1970's and 1980's technology. There is significant inertia in the water management agencies to embark on long-term hardware and software innovation enterprises given limited budgets and the necessity to accomplish studies at hand in a timely manner. The issues confronting agency personnel, regulators and water managers in this River Basin provide exemplars of the same issues found all over the world. Forecast simulation is a poorly evolved capability within the federal, state and local water agencies since it requires real-time access to all data resources needed to run a simulation model with a real-time quality assurance capability to make sure that information being used within the forecast simulation model is reasonable, reliable and meets a minimum threshold of accuracy. Technologies exist to perform these tasks but have yet to be incorporated in any of the simulation models in everyday use. The overriding goal of this Reclamation Science and technology project is to formulate and develop the next generation water supply and water quality forecasting tools that will become a standard for agency and stakeholder use within California and have potential use in water-quality impaired river basins world-wide. These tools will deploy the latest in data and output visualization technologies.

Data visualization capabilities have increased dramatically since the introduction of the Geographic Information System (GIS) which provided the ability to view data both temporally and spatially. Spatial data often lend themselves to visualization because the data are geocoded and can therefore be represented easily on maps and map-like objects (Fotheringham and Wilson, 2007). New developments in GIS technology have fostered new visualization techniques, including outputs of statistical analysis, that have been applied and incorporated as toolboxes for water quality modeling and basin water quality management (Jiang et al., 2012, Kulawiak et al., 2010, Sandy et al., 2009, Velasco et al., 2014, Zhang et al., 2011, USEPA, 2007 and Innovyze, 2013). Some watershed models, such as WARMF (Chen et al. 1970), AnnAGNPS (Binger et al. 2001), APEX (Gassman et al. 2009), GSSHA (Downer and Ogden, 2004), SWAT (Gassman et al. 2007) are integrated with a GIS and have the ability to view input data as well as model results with a common Graphical User Interface and visualization toolbox. Model-based output visualization, data visualization and combined input and output visualization within a GIS framework will be discussed in detail in the following sections.

1.1 San Joaquin Basin applications of a new generation model

Water quality management is a critical issue required to assure sustainable agriculture and communities in the San Joaquin River Basin and the decision making needed to optimize water quality management must increasingly be made in real-time. As global climate change alters the hydrologic conditions of the San Joaquin basin, real-time management of water resources will become an even great challenge. Water flows directly affect water quality in the basin with challenges arising from salts, trace elements (Se, B, Mo, As), nutrients, pesticides, dissolved organic matter, and dissolved oxygen. To maximize water availability, the assimilative capacity of San Joaquin River flows must be optimize to dilute, transform and transport (remove from basin) to meet water quality objectives. As has been demonstrated by ongoing flow and salinity simulation modeling and forecasting programs on the San Joaquin River, integrated monitoring and forecast modeling has the potential to effectively improve the transport of salts from the San Joaquin River Basin while ensuring compliance with State water quality objectives for salinity. In the past decade we have seen the development of sensor networks capable of real-time monitoring of important flow and water quality parameters including water discharge, salt, temperature, and dissolved oxygen. With these basic environmental monitoring platforms in place - monitoring of more difficult-to-measure water quality constituents such as nutrients, dissolved organic matter and sediments is possible to provide a comprehensive water quality monitoring and forecasting program.

Recent advances in remote sensing data have the potential to complement environmental data collected at current installed monitoring stations - however the integration of satellite remote sensing data and resources has yet to be realized. The recent decision by NOAA to put LANDSAT data into the public domain has created significant opportunities for real-time processing of multi-spectral remote sensing imagery that can help track phenomena such as algal blooms in river systems – field verified with in-river continuous chlorophyll sensors. Google's EarthEngine is a similar innovation which among other uses is providing real-time evapotranspiration estimates for large areas within river basins.

Despite the advances in sensor hardware and the decline in sensor costs which has made building networks more affordable – scant attention has been focused on real-time data quality assurance and there are only a handful of commercial companies at have developed software equal to this task. One of the reasons water districts and other private entities discharging directly or indirectly to the San

Joaquin River have been reluctant to share data or make drainage data freely available in the past is the fear that inaccurate data may be used against them in regulatory actions or in litigation. However data sharing is key to the concept of real-time water quality management that has been enshrined in the Water Quality Basin Plan for the San Joaquin River Basin.

Even though environmental sensor costs have declined significantly in the past decade these water quality sondes are still too high to stimulate a similar explosion in sensor applications and use that has occurred in the urban environment. It is only a matter of time before some of the current dominant commercial vendors are pushed side by mass produced products with sensors of equal reliability. Interacting sensor webs, which are being propelled by the rapid expansion of social media may soon penetrate the environmental arena. Our river water quality simulation and forecast modeling tools should anticipate these likely developments and the next generation model should be designed to assimilate these diverse data seamlessly once an acceptable level of data quality assurance has been performed.

Data and model output visualization has also advanced significantly in the past decade. Geographic Information System (GIS) integration is now routine in many watershed water quality models that rely on land-use data. This allows spatial data to be more easily imported and exported as model output. Animation capability has now become routine. Developing movies from multiple stills of model spatial output can be a very powerful tool for promoting process understanding. Radically new visualization ideas that employ statistical analysis of model outputs are also becoming more common such as variants of box and whiskers plots and other means of depicting model uncertainty.

1.3 Existing water quality forecast modeling and simulation tools – in use

It is extraordinary that in the most technologically advanced state in the US that the water quality simulation and forecasting models in use by the State of California and the Federal agencies are as limited and dated as they are. Most are based on codes developed in the 1970's and 1980's and have been adapted and added to over the years so as to applicable to the increasing complex scenario requirements of the present day. The water quality simulation and forecasting model that is in the highest demand for San Joaquin Basin studies at the present time is the WARMF (Watershed Analysis Regional Management Framework) model. This model was an outgrowth of the ILWAS model developed by Chen et al. in the 1970's to examine solutions to acid rain problems in the north-eastern US. The model was one of the most advanced mechanistic models of its day and had little need to simulate groundwater processes since much of the forest land being considered had relatively shallow soil layers on top of underlying bedrock. This conceptual view of the modeling domain has carried through to the current WARMF model which has been applied a number of San Joaquin Basin water quality studies – the cost of which exceeds $4 million. Other models such as HEC-5Q are also in use – however this model has no capability to simulate watersheds – being designed primarily as a reservoir operations model. The model has limited capacity to be integrated with other models in a more comprehensive modeling system.

This review of the basin-scale models in current use has been undertaken to demonstrate the need to take stock of existing codes and undertake a model development effort that takes advantage of the most promising current technologies, addresses known limitations and defects in current tools and anticipates future water quality simulation and forecasting needs.

2. Water Quality Modeling

The TMDL Subcommittee of the American Society of Civil Engineering Environmental Water Resources Institute (ASCE-EWRI, of which co-author Quinn is a member.) is in the process of developing a handbook on TMDL watershed modeling models – this section on water quality modeling is derived from this draft publication (ASCE-EWRI, 2014).

Water-quality modeling is often used to develop the linkage between the sources of pollution and the water quality of a given waterbody. Mathematical models of water quality are used for a variety of purposes, such as for research and as organizational frameworks for the evaluation of environmental data. For regulatory purposes models are most commonly used to estimate the effectiveness of environmental control actions, such as permitting of loads by establishing "cause and effect relationships" between an environmental pollutant load and a standard and criteria. That is models are used to develop a relationship such as in (1 (Chapra 1997) between some desired response such as water quality concentration (C) in some waterbody (e.g. river, lake, estuary) and an external stimulus such as a waste load (W), where the relationship between them (C and W; referred to as assimilative capacity, a) is often a highly non-linear function of the physical, chemical, and biological characteristics of the materials and receiving water.

$$C = \frac{1}{a} W \qquad (1)$$

A common application of such a tool is to determine, given some "desired" C, the load W that could be applied protective of "C", referred to as a wasteload allocation or the total load (allocation of non-point source loads, LA, and point source loads, WLA) in a TMDL. Establishing the WLA and LA is critical not only to permitting but to design (e.g. of treatment facilities) and water quality management.

Decision makers often rely on modeling results and in particular have become interested in the visualization of these modeling results to more effectively communicate and compare alterative water quality and contaminant load management strategies. These visualization tools are becoming useful as a means of evaluating the underlying data being fed into these models to assess risk and confidence in these alternative management strategies. Understanding the problem and all its aspects is of great value in model development.

2.1 Model Selection

As shown in Fig. 1, water quality modeling is embedded within the larger context of the TMDL decision process. The primary function of modeling is to provide a decision support model that can be used in TMDL prescriptions. In particular, the model provides a means to predict water quality as a function of loads and system modifications (Chapra 2003). The water quality modeling process starts with data base development and then model selection based on its data requirement. The latter relates to situations where existing models are inadequate. After selecting or developing the model, existing data are used to construct a preliminary model application. The appropriate modeling approach depends on the project goals as well as the data available for the chosen model application. When there is inadequate data, it is better to focus on a simple water quality model rather than detailed or complex model. Developing a parsimonious water quality model will be useful for urban areas in comparison to other regions due to the lack of water quality data. After selecting or developing the model, existing data are used to construct a preliminary model application. This exercise should include thorough data mining to ensure that all possible historical data are considered.

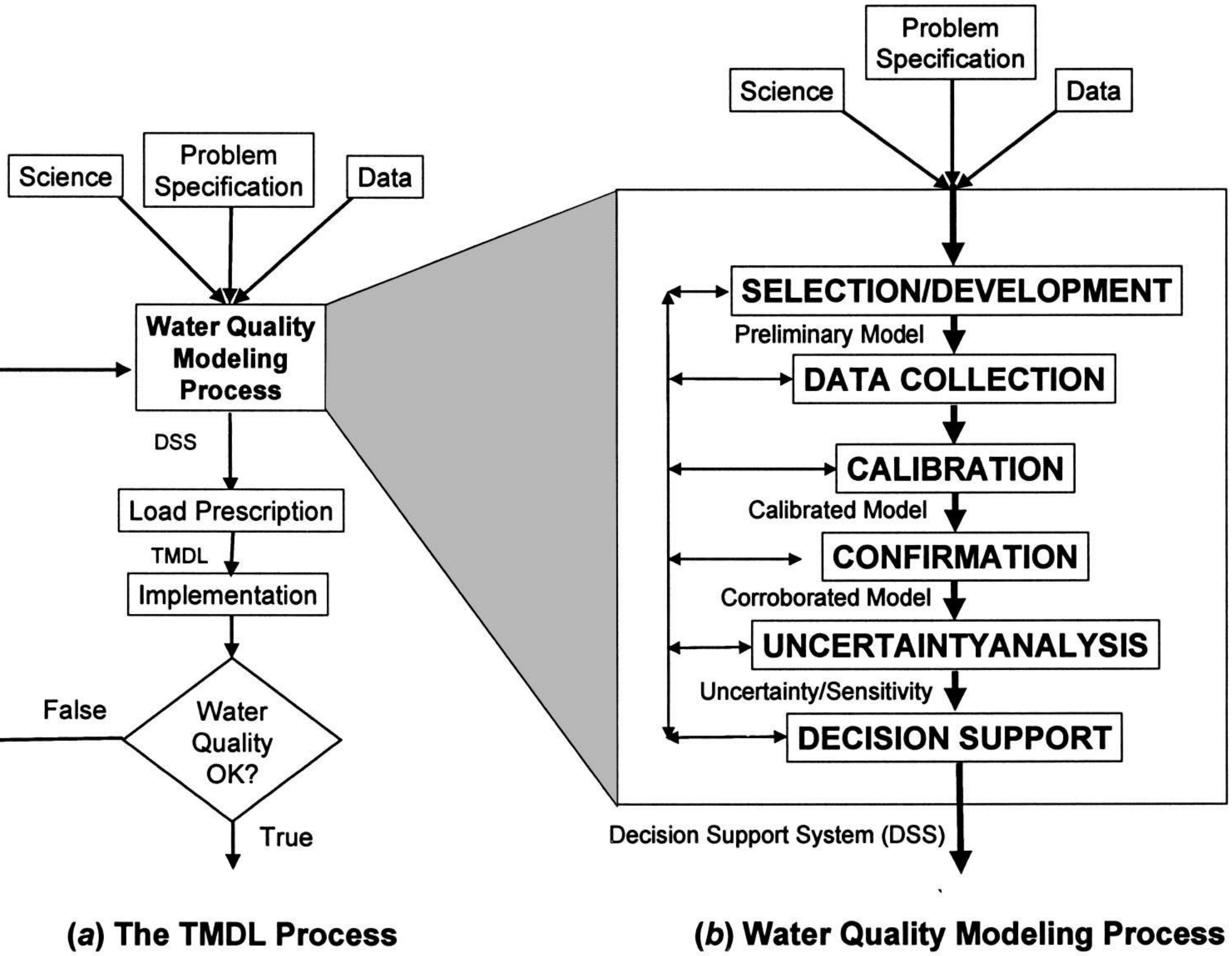

Fig. 1. Water-quality-modeling process (b) within the context of TMDL process (a) (Chapra 2003, ASCE-EWRI, 2014)

A series of examples of mechanistic models applicable to WLA and TMDL studies are provided in the last sections of this document. First, a brief history of the development of these models is presented below in order to aid the reader in understanding the structure and function of those models as well as their capabilities and limitations (ASCE-EWRI, 2014).

One of the first widely used numerical WLA models for rivers and streams was QUAL-II. A brief history of QUAL-II is illustrated in Table 1. A number of versions of the model were developed for various agencies, with the first version for USEPA developed by the National Council for Air and Stream Improvement (NCASI) in 1985. The next version (QUAL2E-UNCAS) included both sensitivity and uncertainty analyses (using First Order Error Analyses, FOEA, or Monte-Carlo algorithms). At that time QUAL2E-UNCAS model (Brown and Barnwell 1987) became arguably the most widely used WLA model in the world. The model was initially written for the MS DOS operating system (Microsoft Disk Operating System) with ASCII input files. In addition to the increased flexibility or the numerical model,

Table 1. Brief History of the Evolution of QUAL2E

QUAL-I (1970)	
F.D. Masch and Associates for Texas Water Development Board (TWDB)	
DO, BOD, Conservative materials	
QUAL-II (1972)	
Water Resource Engineers for EPA	
Algae, Nutrients, Non-conservative	
QUAL-II/SEMCOG (1978)	
CDM/WRE for Southeast Michigan Council of Governments	
Refinements to QUAL-II; Steady-state solution	
Diurnal averaging for algae and temperature	
QUAL-II/NCASI (1980)	
Detailed documentation and commentary by NCASI	
Code corrections	
QUAL2E (1985)	
NCASI for EPA	
Enhancements to Algae-Nutrient-DO interactions, hydraulics, temperature and output formats	
Microcomputer application	
QUAL2E-UNCAS (1987)	
Uncertainty analysis, sensitivity, first order, Monte Carlo	
Reach variable climatology	
QUAL2EU(1990)	
Pre and post processors	
Graphics	
QUAL2E in USEPA BASINS (Version 3, 2001) and CEAM Distribution	
Microsoft DOS, Windows 3.1 and OS2, 95, 98	
	USEPA Center for Exposure Assessment Modeling: "The DOS version of model and associated files can be downloaded from the CEAM home page"
Windows XP and NT (app. 2004)	
	USEPA Center for Exposure Assessment Modeling: "The above version does not work under Windows-NT/2000/me/XP. A version of the program that is compatible with Windows NT and 2000 only is available: Qual2e for Windows NT/2000 (q2e_nt.zip) (Size=1.1 mb). This NT/2000 version runs as a stand-alone separate from the BASINS system. Also, this version is not compatible with Windows XP. There are currently no plans to create an XP compatible version of QUAL2E for Windows."
	QUAL2E subsequently removed in 2004 from BASINS and EPA websites

one major advantage over the analytical DO-sag models was that it allowed estimation of water temperatures as a function of meteorological conditions, prediction of diel variations (over a 24-hour period) rather than just the "average" concentration and in including turbulent mixing (neglected in the

DO-sag analytical models). However, applicable conditions remained the same (steady-state flows, low flows).

One of the other advances impacting models and model development during the 1960's and continuing today was the personal computer (PC). With improved operating systems, more "user friendly" working environments were commonly developed, a phase of modeling that has been called - the MTV phase. During that phase considerably more effort and resources were often spent on developing graphical user interfaces (GUIs), rather than improving the models themselves. The most common PC operating systems for that software were Microsoft Windows operating systems. With increasingly frequent "advances" in PC operating systems, such as from Windows 3.1 to Windows 95, 98 and NT the capabilities for running under primitive MS DOS were reduced finally removed. Data and model visualization also improved substantially in this period with the advent of Geographic Information Systems (GIS) and the ability to animate multiple realizations of model output, as previously described.

2.1 Steady-Flow Water Quality Models for Lakes and Estuaries

During the period of the 1970's there were a variety of models and modeling systems developed to relate algal concentrations (and oxygen) to nutrient loads and toxicant concentration to industrial loads or loads mostly from superfund sites. In general most of these models assumed, based on field data, some constant flow and flow path (e.g. for multi-dimensional models). For estuaries, river flows were assumed constant and tidal flows represented with a tidally averaged dispersion coefficient (tidally averaged models, see Martin and McCutcheon 1999). Many of the models used during this period have been described in Chapra and Reckhow (1983), Thomann and Mulleer (1987), and Chapra (1987).

A popular water quality simulation model developed during this period was WASP (the Water Analysis Simulation Program). WASP is a "Box" model in that it represents a system as a series of completely mixed reactors which can be stacked in various ways to represent 1, 2 or 3-dimensional systems. The original version of WASP was developed using a very well-designed modular system consisting of a transport model to which various water quality sub-models may be attached. The original version of WASP was developed by Di Toro et al. (1983) for application to nutrients in the Great Lakes. Robert Ambrose, with the USEPA, then took the model and added toxicant routines resulting in the TOXIWASP model (Ambrose et al. 1983). The models were initially merged with the release of WASP Version 3 in 1986 (Ambrose et al. 1986). The present WASP model (Version 7.5 released in 2011) includes routines for simple and advanced eutrophication, organic toxicants, metals and mercury and is the most widely used dynamic model of its type in the world. While in most of the early applications flows were specified to the model, most modern applications of WASP are to dynamic flow conditions.

2.2 Dynamic (Time-Variable) Water Quality Models

Many of the early models were based on constant (steady) flows for some assumed critical condition (e.g. the 7Q10 flow for rivers). One of the limitations of many of the early models and model applications was the use of very simplified or descriptive hydraulics. The flows were often based on field measurements or simplified hydraulic models. One common method as used in QUAL2E was using rating relationships between flow and a characteristics such as depth or velocity (e.g. $D=aQ^b$, where D is depth, Q flow and "a" and "b" are empirical coefficients) or Manning's equation. Manning's equation is based on the assumption of steady-uniform flow (time and spatially invariant) hydraulic conditions (e.g. flows, depths, velocities), so would for example underestimate depths in backwater areas.

Steady-flow hydraulic models (commonly referred to as step-backwater models) were also developed during this period which could supply hydraulic information to riverine water quality models (e.g. QUAL2E, QUAL2K). For example, HEC-2, the Water Surface Profiles program, originated from a step-backwater program written in WIZ (a version of BASIC) by Bill S. Eichert in 1964. In 1966 the first FORTRAN version of HEC-2 was released by the Hydrologic Engineering Center (HEC) under the name "Backwater Any Cross Section." HEC-2 was widely used and then updated resulting in HEC-RAS in 1995. The original HEC-RAS was still for steady-flows until the incorporation of the unsteady UNET model developed by Dr. Bob Barkau. However, it was not until release Version 4.0 in 2008 that water quality routines were included in HEC-RAS.

An issue during the 1980's was dynamic hydraulic conditions, and numerous efforts were made to couple hydrodynamics and water quality. There were basically two approaches, to either include water quality routines in the hydrodynamic model or have the hydrodynamic model write out linkage files (with the time-variable hydraulic characteristics) subsequently read by the water quality models. Examples include the linkage of the DYNHYD (Ambrose et al. 1984) hydrodynamic model and WASP, such as in the application to the Delaware Estuary by Ambrose (1987). Other examples include the development of the CE-QUAL-RIV1 model (Environmental Laboratory 1990). That model consisted of a separate hydrodynamic and water quality model, where the hydrodynamic model wrote a linkage file containing the hydraulic predictions which was then read by the quality model (with kinetics based on QUAL2E). The model was originally developed and designed for application to Corps of Engineers projects, such as to evaluate the impact of reservoir releases. For example, initial versions of RIV1 either did not include lateral flows (such as due to other tributaries, point or non-point sources) or held them constant with time. That is an important consideration for any model applicable to TMDLs, as discussed later. Similarly, during that period the original version of the two-dimensional (laterally averaged) CE-QUAL-W2 (Corps of Engineers, Quality Model for 2-dimensional waterbodies; Environmental and Hydraulics Laboratories 1986) was developed. Today the trend continues and it is now routine (but still not a trivial exercise) to couple (directly or indirectly) hydrodynamic and water quality models.

Also during the period a number of sediment transport models were developed, typically for purposes other than water quality, such as for sedimentation design or scour predictions. Computerization also allowed significant advances in the development of hydrologic models, primarily for predicting runoff and flooding, with the development of the first comprehensive model the Stanford Watershed Model (Crawford and Linsley 1966). During this period the widely used HEC-1 model was developed by the USACE Hydrologic Engineering Center (along with HEC-2; HEC 1973). Also, the SWMM, Storm Water Management Model (Huber and Dickson 1988) was developed for the USEPA for runoff in storm sewer systems. The HSP Quality (Hydrocomp 1977) was developed as a derivative of the Stanford Watershed Model. The Hydrologic Simulation Program Fortran (HSPF) was developed integrating the field-scale EPA Agricultural Runoff Management model (ARM, Donigian and Davis 1978) and the EPA Nonpoint Source Runoff model (NPS, Donigian and Crawford 1979) models. HSPF became one of the first models for continuous simulation of water quality of runoff at a watershed scale along with hydrologic flows.

Similarly, the USDA Agricultural Research Service (USDA -ARS) developed a series of models including (Figure 1):

- The Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel et al., 1980),
- the Groundwater Loading Effects on Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987), and
- the Environmental Impact Policy Climate (EPIC) model (Gassman et al., 2005; Izaurralde et al., 2006, originally called the Erosion Productivity Impact Calculator Williams, 1990).

These models were incorporated into the Simulator for Water Resources in Rural Basins (SWRRB) model (Williams et al., 1985; Arnold and Williams, 1987) designed to simulate management impacts on water and sediment movement for ungaged rural basins across the U.S. and which evolved and were merged into the present Soil and Water Assessment Tool (SWAT model, Gassman et al. 2007).

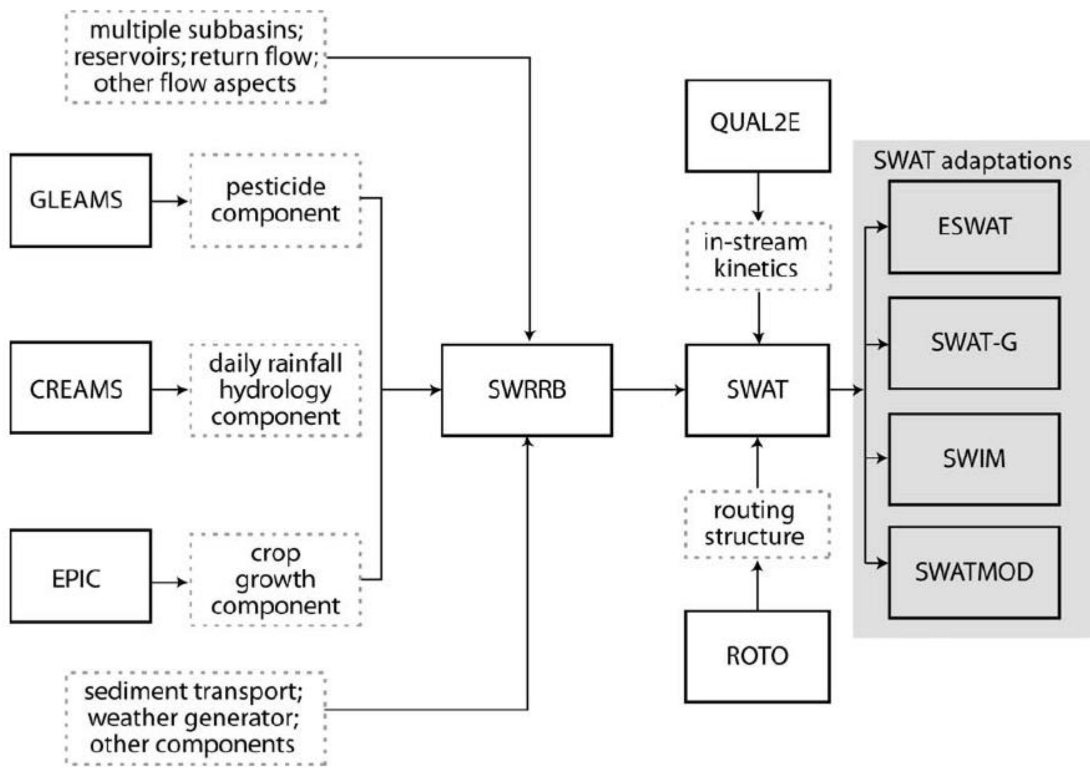

Figure 2. Schematic of SWAT developmental history, including selected SWAT adaptations (from Gassman et al. 2007).

2.3 TMDL specific water quality simulation models

The Clean Water Act (CWA) under section 303(d) requires that all states to develop and implement Total Maximum Daily Loads (TMDL) for their impaired water bodies (those failing to meet water quality standards) and water bodies threatened to become impaired (Martin and Kennedy 2000). During the first 30 years following the CWA the focus was on point sources. However, for those waterbodies which following implementation of point source controls that still do not meet basic water quality standards (are impaired) TMDLs are required which includes allocation of both point source loads (the Wasteload Allocation or WLA) and non-point source loads (the load allocation or LA).

For TMDLs, as with point source controls, water quality models (e.g. (1) are used to establish the relationship between loads and effects in order to determine the allowable TMDL (WLA + LA + a margin of safety). Formerly, the WLA was determined (such as for dissolved oxygen) for streams and rivers based on low flow conditions (e.g. the 7Q10 flow) and summertime temperatures. However, for LA loads resulting primarily from stormwater, the steady-low-flow paradigm is no longer applicable. The conditions then are often dynamic, so that models used to estimate the TMDL must then often also be dynamic. In addition, the LA results from flows and loads from the watershed. That requires application of a watershed model.

There are many cases where very simplified approaches are appropriate for TMDLs. One example is where the assimilative capacity is solely a function of flow (Q), so that "a" in (1 is equal to Q, and then the allowable W=CQ. There are other cases where the simplified steady-flow models (e.g. DO-sag models) are appropriate. However, for many cases where continuous simulations of point and non-point source flows and loads are required a TMDL modeling system must consist of linked models of the watershed, receiving water hydrodynamics and receiving water quality. Therefore the paradigm shift is from a steady-flow point source and in-stream environment to the watershed. TMDLs are essentially driving the watershed approach to water quality management.

The TMDL modeling approach then often required the linkage of watershed, hydrodynamic and water quality models. In some cases atmospheric loads or models were also required (e.g. for mercury where atmospheric deposition is often a significant source). Groundwater models were also required in some applications to estimate loads from the groundwater or surface/groundwater flow interactions. The issue was that in many cases these models were not designed to work together and/or not designed for the continuous simulations required for TMDLs. The result was often a "Patchwork Quilt" of models, a term commonly used to refer to "a collection of miscellaneous or incongruous parts; a jumble" as opposed to a seamless integrated modeling system designed for the purpose of establishing TMDLs.

One example described above was the QUAL2E model, and how it was removed from BASINS and distribution by EPA. BASINS (Better Assessment Science Integrating point and Nonpoint Sources) is a multipurpose environmental analysis system designed for use by regional, state, and local agencies in performing watershed and water quality-based studies, such as TMDLs. A question could be why it was ever included in BASINS, since QUAL2E is based on the assumption that flows are constant with time (steady flows) so cannot be used to simulate the effects of time-variable non-point source runoff (i.e. for BASINS, an incongruous part). Another issue is that in many cases while watershed and water quality models both simulate water quality, the water quality variables are often different requiring "translation" from one model to the next. The linkage of hydrodynamic and water quality models is also often problematic since the two models are rarely designed together (e.g. the basic structure and numerical techniques often differ) and often maintaining a mass balance is problematic. Mass balance is crucial for water quality models (which are often called mass balance models). In addition, linkage of models of different time and space scales creates a new set of issues that are often only poorly resolved. The models can also not be applied in a totally "feed-forward" manner, since errors or inadequate predictions or the watershed, or hydrodynamic, models are often only identified during the application of the model of water quality which raises issues in the design and management of model applications. Also, identification of the "critical conditions" for the assessment of the TMDL is much more problematic that the relatively simple 7Q10 low flows.

Many of the problems and issues associated with models and modeling systems for TMDLs have been resolved over the last decade, but many issues remain. In many cases the issues impacting the selection and application of models are site and chemical specific. The approach and methods can also vary depending whether as single reach or watershed TMDL is appropriate, where a watershed TMDL is the result of a holistic approach to the simultaneous development of multiple TMDLs for hydrologically linked impaired segments (USEPA 2008).

3. Comparison of water quality simulation and forecasting models for the San Joaquin Basin

The models described in the following section are applicable in whole or in part to the salinity TMDL application in the San Joaquin Basin.

Here we summarize the available physically based watershed models that are comparable to WARMF. The models discussed are: WARMF, AnnAGNPS, APEX , GSSHA, LSPC/HSPF, SWAT, SWMM and WAMview. These eight were selected from a list of more than 30 hydrologic models. For the purposes of comparison to WARMF we focus on watershed scale water quality models that are publically available. Therefore, models not designed for continuous simulation (i.e. event models) or requiring long time steps (i.e. monthly or annual) were eliminated from consideration. Similarly, one dimensional and field scale models were filtered, and only physically based models with water quality capabilities were included. Finally, proprietary models and models with insufficient documentation were also excluded.

The section that follows summarizes the capabilities of WARMF and the seven additional models selected above. For each model the discussion includes: (1) general approach to surface and subsurface flow, (2) land surface processes, water management capabilities and approach to water quality modeling, (3) pre and post processing tools and user interfaces included with the model, and (4) comparison to WARMF.

3.1 Watershed Analysis Risk Management Framework (WARMF)

WARMF is a lumped physical hydrology model that has been demonstrated for study areas as large as 16,000 square miles. It calculates overland flow based on precipitation and groundwater accretions and subsequently routes streamflow between sub-basins using the kinematic wave equation. Reservoirs are simulated through a link with the CE-QUAL-W2 model, however WARMF cannot simulate wetlands. While it does not simulate deep groundwater, a dynamic physically based soil moisture water balance is simulated. This includes lateral flow through the soil layers using the Darcy equation and two-way exchanges between surface water bodies and the unsaturated zones of the soil layers.

At the land surface, potential evapotranspiration is calculated using meteorological variables and the Hargreaves equation. Actual evapotranspiration is subsequently determined based on water availability. WARMF includes a number of built-in land cover types and it’s possible for the user to add custom types if needed. Snow melt and accumulation are simulated based on physical processes. The model includes many options for agricultural management. The user can specify irrigation rates and source for each catchment as well as fertilizer application rates. Built in BMPs include livestock fencing, street sweeping, buffer zones, detention ponds and changes in tillage. WARMF uses a physically based approach for water quality modeling based on geochemistry and mass balance. Within each model element WARMF assumes Continuously Stirred Tank Reactor (CSTR) model. It can simulate both point and non-point sources for many constituents including nutrients, BOD, pathogens, suspended sediment pesticides, metals and salinity and it has a built in module for TMDL calculations.

WARMF has a GIS based GUI that is used to specify model parameters and run simulations. Although the model does not include input databases, the majority of the required inputs can be populated from publically available datasets. Also, the BASINS tool can be used to define sub-basins and setup a WARMF domain. Currently WARMF does not have the ability to automatically incorporate all real time data or retrieve data without some form of intervention from web servers. Model results are stored in an output database that is linked to GIS. This linkage allows the user to view time series outputs and look at spatial results by watershed or reach.

Overall, WARMF is a sophisticated water quality model that has been well proven in many real world basins. Using a physically based approach WARMF can simulate complex domains with heterogeneous land cover types and management practices. Also, the GUI allows users to easily modify scenarios and the TMDL module facilitates easy analysis of regional scale loadings. Some of the biggest limitations of the WARMF model stem from its simplification of the groundwater system. WARMF cannot simulate lateral groundwater flow below the soil layers, agricultural tile drains or wetlands.

3.2 Agricultural NonPoint Source pollution model (AnnaAGNPS)

AnnaAGNPS is a lumped physical hydrology model. It divides watersheds into homogeneous land areas using the TOPAZ input generator and has been used for daily simulation of large watersheds. It's hydrologic approach is based on water balance. Runoff is generated using the curve number approach and flow in river reaches is calculated using the kinematic wave equation and Manning's equation. However, it is not designed to simulate wetlands or reservoirs. Its treatment of the subsurface is similar to WARMF. It has a soil moisture simulator that calculates the moisture balance in two soil layers. This module calculates lateral flow using Darcy's equation, losses to groundwater and changes in runoff as a function of soil moisture; however there is no simulation of deeper groundwater.

Surface evapotranspiration, snow processes, crop growth and erosion are also simulated. Water management capabilities are similar to WARMF with two primary differences, AnnaAGNPS does not simulate surface water diversions but it can include agricultural drains. As with WARMF water quality simulations are based on conservation of mass. Soluble nutrients, from both point and non-point sources, are partitioned between surface runoff and infiltration. Loadings can be identified at their source and tracked through the watershed. However, AnnaAGNPS is more limited than WARMF in the number of constituents it can simulate and it is not designed to calculate TMDLs.

AnnaAGNPS also includes an integrated GIS interface. Pre-processing tools are included in the GIS interface and inputs can also be exported in CSV format to allow for spreadsheet manipulations. In addition there is an output processor that can be used to generate result summaries in tabular or GIS forma. As with WARMF the AnnaAGNPS can't automatically incorporate real time data or retrieve data from a web server.

Overall AnnaAGNPS has many capabilities that are similar to WARMF. However it is more limited in its water quality simulations and does not have the ability to calculate TMDL's automatically. For example, point sources are limited to a constant loading rate for the entire simulation period and it currently does not list salinity as one of its water quality constituents.

3.3 Agricultural Policy/Environmental eXtender Model (APEX)

APEX is a lumped physical hydrology model designed primarily for analysis of non-point source agricultural loadings. It simulates flow through channels, reservoirs and floodplains using variable storage coefficient and Muskingum methods. Surface runoff can be calculated either using runoff curves or the Green and Ampt equation. As with WARMF, APEX simulates soil moisture and infiltration but no lateral groundwater flow. Water that infiltrates from the surface can be stored in the soil profile, percolate to the groundwater evapotranspire to the atmosphere or be routed later through the subsurface or through tile drains. APEX can simulate fluctuations groundwater depth but there are no direct links between water table calculations and other hydrologic processes.

As noted above APEX is designed for agricultural areas and has many cropping and management options including: irrigation methods, drainage, furrow diking, buffer strips, terraces, fertilization, manure management and changes in tillage. There are five options for potential evapotranspiration calculations and nearly 100 different crops are included in the model. In addition to user specified irrigation rates, similar to WARMF, automatic irrigation triggered by water stress can also be implemented. Also, irrigation water can be supplied both from surface water diversions and by pumping the aquifer. Water quality calculations are physically based and incorporate leaching, surface runoff, subsurface flow, volatilization, mineralization, immobilization and partitioning between solute and sediment phases. While it does include carbon, nitrogen and phosphorus cyclingAPEX does not currently include salinity and is not designed to calculate TMDLS.

APEX generates standard output files including time-series files and spatially distributed results. It does not have a user interface directly incorporated into the model, however there is an ArcGIS-ArcView extension called ArcAPEX that is designed to handle model inputs and outputs.

In summary, APEX has some advantages over WARMF. It has some improved groundwater simulation capabilities (i.e. groundwater pumping and tile drains) and includes more land cover types with dynamic crop growth and the option to do moisture dependent irrigation. It also has a wide array of land management practices and there are many options to simulate managed grazing. However, APEX does not have a TMDL module and there is no GUI for the model itself, you have to download the ArcGIS tool. Finally, it doesn't handle as many water quality constituents as WARMF and it doesn't calculate salinity.

3.4 Gridded Surface Subsurface Hydrologic Analysis; distributed-parameter, process-based model (GSSHA)

GSSHA is a gridded hydrology model that can be used to simulate large watersheds. It simulates 2-D overland flow with 1-D streamflow generated from spatially and temporally varying precipitation. Overland flow is routing through the channel network using the diffusive wave equation and lake storage is calculated using level pool routing. GSSHA has some advantages of WARMF with respect to groundwater simulation. It includes 1-D infiltration and 2-D groundwater flow with a full coupling between groundwater, shallow soils and overland flow. 1-D infiltration is based on the Green and Ampt equation or 1-D vertical Richard’s equation. Lateral groundwater flow is calculated based on vertically averaged saturated flow and flow in the vadose zone is simulated with 1-D Richard’s equation. This approach allows GSSHA to simulate wetland and peat layer hydraulics as well as stream aquifer interactions.

GSSHA includes land surface processes like evapotranspiration and snow processes similar to WARMF using an energy balance approach. It incorporates spatially variable land cover by grid cell and can calculate overland erosion as well as sediment transport. While the model does include land management practices, it is more limited that WARMF in its agricultural options. Tile drains, diversions and groundwater pumping can be simulated but irrigation and fertilizer application are not included. There are no built in BMPs but users can implement their own by adjusting other parameters. Water quality can be simulated either using simple constituents or the full nutrient cycle. Many constituents are included and both point and non-point sources are allowed; however there is no module for TMDL calculations.

GSSHA is coupled with the Watershed Modeling System (WMS) interface for pre and post processing. WMS can be used to delineate watersheds, setup domains and view outputs. Model outputs are automatically formatted to interact with WMS. Outputs include gridded time series for many variables and depth and discharge time series can be produced for any node in the channel. However, like WARMF, WMS does not have the ability to automatically incorporate real time data or retrieve data from a web server.

Overall, GSSHA has some advantages over WARMF with respect to groundwater and wetland processes. However, it is designed more as a hydrologic model than a water quality model for agricultural settings. It does not include irrigation or fertilization and is not designed to calculate TMDLS.

3.5 LSPC/HSPF

The Loading Simulation Program in C++ (LSPC) is a watershed simulation model that is derived from the hydrologic Simulation program Fortran (HSPF). It is designed to handle large-scale watersheds and can handle systems with over 1,000 sub watersheds. It uses many of the same algorithms as the HSPF model but with and updated streamlined approach. Overland flow is simulated using modules originally developed for HSPF. Overland flow is determined from functional tables for depth discharge relationships and flow is routed using the kinematic wave equation assuming completely mixed reaches and unidirectional flow. LSPC can simulate lakes and reservoirs but there is no discussion of wetland simulation. As with surface water, LSPC simulates groundwater using HSPF modules. Water from the surface that infiltrates can be stored in ‘active groundwater storage’ which can then move laterally and contribute to baseflow, percolate to the deeper groundwater or leave the groundwater through plant uptake.

Evapotranspiration is also calculated using HSPF modules first potential evapotranspiration is calculated based on meteorological variables, next this value is adjusted to actual evapotranspiration based on the water availability in both the surface and subsurface. LSPC is a lumped model, however each sub watershed can be represented by multiple land units with a range of pervious and impervious land use types. Agricultural management practices such as irrigation and water diversion are not covered in the LSPC documentation. Fertilizer application, tile trains and BMPs are also not included in the model, although the user can specify load reductions from point and non-point sources directly. Water quality in streams is simulated for many constituents using advection and decay processes. LSPC also includes accumulation and wash off from land surfaces and has a separate module for TMDL calculations.

LSPC is part of the TMDL toolbox developed by the EPA and as such is easily incorporated with other EPA tools for model setup. Model domains can be automatically extracted from an underlying access database and the Watershed Characterization System (WCS) extension can be used for pre-processing. LSPC also includes and GIS interface with a control center for launching scenarios and its outputs are directly compatible with ArcView. Outputs are stored in an Access database and there are analysis tools for reviewing time series and spatial outputs.

Overall, LSPC compares quite closely with WARMF with respect to its physical hydrology capabilities. It has a built in TMDL module and is designed to analyze point and non-point source loading. Also, as a part of the EPA TMDL toolbox, it is well supported and includes pre and post processing tools as well as a GIS interface. However, its biggest limitation is that it doesn't have many built in land management features and there is no discussion of irrigation practices or fertilizer application.

3.6 SWAT

SWAT is a lumped physical hydrology model that was developed to quantify the impact of land management practices in large, complex watersheds. It simulates physically based overland flow divided between a land phase and a routing phase. Runoff from land surface can be calculated using the SCS curve number procedure or the Green and Ampt equation. Routing is based on the Muskingum method and includes transmission and evaporation losses in addition to bank storage. SWAT is capable of simulating both lakes and wetlands and it also simulates subsurface storage and flow. In the subsurface, the top two meters are designated as soil and are modeled with a kinematic storage equation. Below the soils there are two aquifer systems, a shallow unconfined aquifer and a deep confined aquifer. Water infiltrates from the surface to the soil layer based on soil moisture. From the soil layer water can flow laterally to the river or percolate down and partition into the aquifers. Groundwater can also be discharged to the river from either aquifer as baseflow.

At the land surface SWAT calculates potential evapotranspiration using one of three methods. Actual evapotranspiration is adjusted from PET and accounts for interception, bare soil sublimation and evaporation. Snow and erosion processes are also included in the model. SWAT has the ability to simulate a broad array of management practices. For example timing of tillage, fertilizer application and irrigation rates can all be controlled by the user. Water for irrigation can be diverted from surface water sources or pumped from one of the aquifers. Similar to WARMF, SWAT uses a physically based approach to water quality simulation. It includes the movement, degradation and transformation of many constituents with special focus on agricultural constituents like nutrients, pesticides and algal growth. It can simulate both point and non-point sources, however it does not have a TMDL calculator.

SWAT has a number of pre and post processing tools. User interfaces have been developed in Windows, Grass and ArcView. In addition, inputs can be generated using the BASINS program which includes a GIS database and a web data download tool. For post processing SWATPlot and SWATGraph can be used to view time series and spatially distributed results can be mapped in GIS.

SWAT is one of the most advanced watershed simulations tools of its kind and has many of the same capabilities as WARMF. Its primary advantage over WARMF is its' ability to simulate groundwater below the soil and wetlands. The biggest limitation for SWAT as a stand-alone model is the lack of visualization capabilities. However, this is largely overcome through tools like SWATPlot and its incorporation into the BASINS system.

3.7 Storm Water Management Model (SWMM)

SWMM is a lumped model designed to simulate regional water systems, primarily in urban areas. It conceptualizes the domain as a network of nodes and links consisting of conveyance, storage and treatment units that transport water. Inputs to transport network come from surface runoff, interflow dry weather flow or hydrographs. Flow in conduits is modeled using Manning's equation and kinematic or dynamic wave routing. Lakes and reservoirs are simulated as storage units in the network, however it is not possible to simulate wetlands. Groundwater is conceptualizes as a compartment in the model. It receives infiltration from the land surface and transfers part of this inflow to the transport compartment as interflow. The groundwater system is simulated using an aquifer objects that can account for groundwater surface water exchanges but not lateral groundwater flow.

As noted above, SWMM is primarily designed to simulate urban watersheds. The user defines 'land uses' (e.g. residential, commercial, industrial, undeveloped), rather than 'land cover' types. Evaporation is calculated from standing water on the land surface or water in storage and there is no transpiration.

SWMM does include several BMPs, but these are mostly related to urban development and not agriculture. Similarly, SWMM does not have the capability to simulate irrigation, groundwater pumping or fertilizer application. With respect to water quality analysis, SWMM can simulate the transport and buildup of many constituents. The user specifies chemical concentrations in rainfall, groundwater, inflow, dry weather flow as well as first order decay coefficients for every constituent. Chemical build up and wash off is determined by land use and conduits are treated as continuously stirred tank reactors.

SWMM has an integrated GUI that allows users to define their system using visual objects that are mapped in the SWMM workspace. Although, the GUI can help the user define their system sub catchments and drainage points must be determined beforehand. Model outputs are generated in binary files and the GUI can be used to perform statistical analysis and create time series plots, profile plots and tables.

While the SWMM model is able to simulate complicated regional domains, there are two major limitations. First, it was primarily designed for urban stormwater runoff so it doesn't have many agricultural options. Second, it is highly parameterized and is less physically based than some of the other watershed tools. However, its main advantage is the GUI that allows users to setup domains using visual objects and to post process results easily from the same interface.

3.8 Watershed Assessment Model (WAMview)

WAMview is a grid-based watershed simulation model that is especially designed to model areas with groundwater flow. It simulates dynamic overland flow routing using Manning's equation and attenuates flow based on flow rate, path and distance traveled. It can simulate lakes and reservoirs and has a sub-model for wetland simulation. Shallow groundwater flow is simulated with the Bousinesq equation for shallow saturated groundwater flow. There is infiltration from the land surface to the groundwater but no re-infiltration of runoff once it has been generated and no exfiltration of groundwater to the surface.

Evapotranspiration can be modeled in several ways depending on the land use types within the domain. Snow processes are not simulated but erosion is included. WAMview can model BMPs such as stormwater treatment areas and reservoir assisted stormwater treatment areas. However, its agricultural abilities are limited. It does not simulate irrigation, fertilizer application or groundwater pumping. Water quality can be modeled using spatial assessment based on impact indices or with detailed hydrologic and contaminant transport modeling depending on the constituents being considered. Water quality constituents modeled include, soluble phosphorus, particulate and soluble nitrogen, total suspended solids and BOD. Although it does not have a separate TMDL module, WAMview has been used for TMDL calculations of phosphorus loading.

WAMview has a model interface written in ArcView that includes several map coverages. This allows the user to create and modify scenarios in GIS although it not possible to automatically incorporate real time data or retrieve data from web servers. Model outputs are automatically formatted for ArcView. Outputs include time-series outputs at source cells, sub-basins and individual reaches including loading and attenuation. Results are generated on a grid cell basis and spatial results can be plot be grid cell, sub-basin or stream reach.

One of the biggest strengths of WAMView is its GIS interface. It is well suited to capture spatial detail for large regional scale domains. However, it is also limited by a number of simplifications. In general it is physically based, but there are also many parts that are highly parameterized. For example, it has a simplified approach for cell-to-stream water and solute delivery. Also, it has limited capabilities with respect to agricultural management practices. Finally, documentation is limited and it is difficult to determine the precise methodology.

3.10 Model summary spreadsheet

A summary comparison of the features of the water quality models described above is provided in Appendix A. Consistent with the approach taken above – the WARMF-SJR model is used as the basis of comparison.

4. Stand-alone data visualization tools and GIS-based data visualization

Environmental sensor networks have become easier to deploy in the past decade. YSI-EcoNET is an example of a web-based real-time data collection and communication system which allows users to graphically visualize sensor data that can be accessed by clicking on the point location of the monitoring station of interest. As previously mentioned the major limitation of this type of system is that it displays data from one station at a time and has no ability to combine or transform data – such as by multiplying flow and EC (salinity) together and applying a conversion factor to change cfs-uS/cm to tons per day of salt load. However the site is particularly good at providing real-time access to individual sensor data that are transmitted every 15 minutes to a central data hub and from which they can be downloaded.

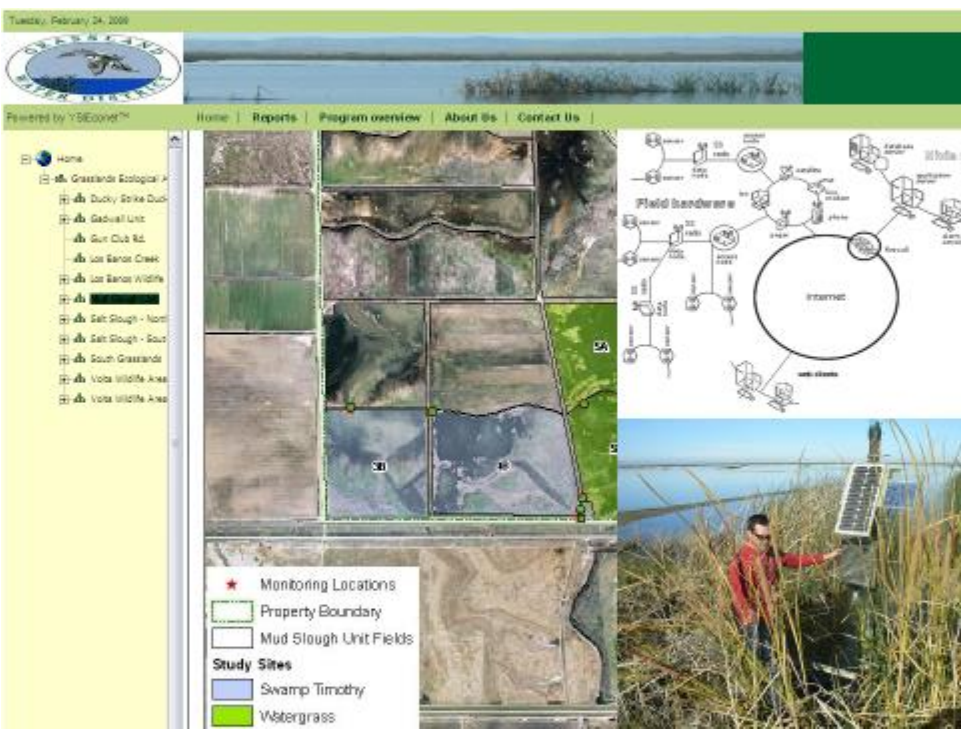

Figure 3. YSI-EcoNET website. Real-time (15 minute) flow and EC data can be accessed by hovering over (or selecting) a monitoring location from the Google Earth data storage site. Real-time data visualization is customizable – data can be viewed as graphical objects (such as a speedometer dial or thermometer reading). Time series data as line graphs or bar charts.

The major limitation of the YSI-EcoNET site (previously described) is that data cannot be combined to estimate important factors such as salt load. In some instances salt loading information is required at sites where no monitoring station exists – data from adjacent sites can often be combined to estimate flow, EC and salt load at that site. This feature is also useful to provide a check on estimating values by creating occasional redundancy within the monitoring network. Addressing this limitation was the major motivation for the Visualization Tool, developed in close cooperation with the Grassland Water District (GWD) and designed to provide information of flow, EC and daily salt load along major conveyances within the District. Each channel segment is associated with a given monitoring station that may be upstream or downstream of the particular line segment and the data associated with the channel reach can be toggled between color ramps for flow, EC and salt load by selecting the check box on the left panel. Short line segments are indicative of inflow into the channel or diversion out of the channel close to the location of the monitoring station. Use of the Visualization Tool provides the GWD with current data and the last 30 days of hourly EC, flow and salt load data that can be animated using the top right scroll bar – showing trends in each parameter within the 45,000 acre District domain and providing decision support for salt management activities.

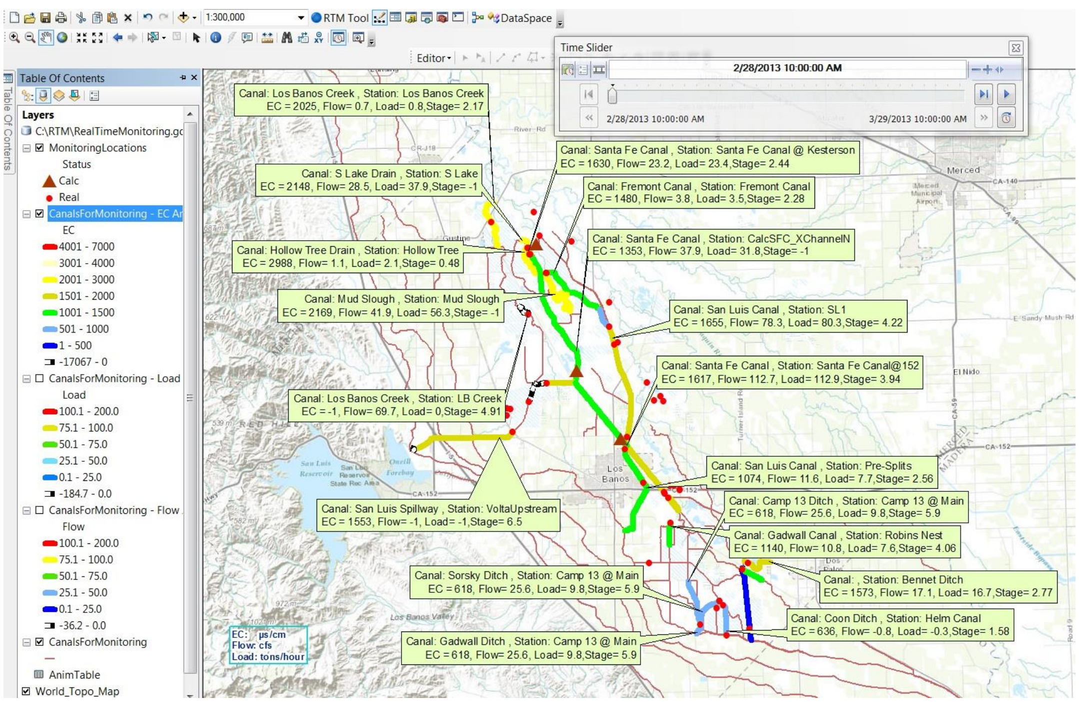

Figure 4. Data visualization tool showing colorized channel segments depicting either mean hourly flow, EC or daily mean salt load within the channel network.

Using some of the same ESRI MapObjects libraries and data parsing techniques deployed for the GWD project – the 2014 Reclamation Science and Technology Program project is in the process of developing a similar data visualization and decision support system for the entire San Joaquin Basin.

5. Conclusions

The review of water quality models focused on candidate models which might serve as a long-term replacement for the WARMF-SJR water quality model or a foundation for the development of a next-generation model. None of the models reviewed is sufficiently customized at the present time to be a viable candidate the replace the current WARMF-SJR model for salinity TMDL analysis and for salt assimilative capacity forecasting. The SWAT model comes closest to replicating the features of the current WARMF-SJR model. The SWAT model has other distinct advantages which would suggest its primacy as an excellent platform to build upon to develop the next generation flow and water quality simulation model and a long-term substitute for the WARMF-SJR model. The first is that the model and model source code reside in the public domain – model development has been undertaken by a consortium of code developers under an Open-Source Licensing agreement. In the case of WARMF – the model itself is downloadable from an EPA website as are model applications such as the San Joaquin and Sacramento WARMF models. However the model source code is proprietary and can be used under special license from Systech Water Resources Inc. The second important advantage offered by the SWAT model is the ability to simulate the hydrology of the groundwater system in a more discrete manner. The WARMF model lumps many factors such as subsurface tile drainage – which is not as important in non-salt affected areas and in upland watersheds. However subsurface drainage is of significant importance for west-side irrigated agriculture and it is important to be able to track the fate of saline deep percolation as a result of irrigation applied water.

The WARMF-SJR model has been updated and upgraded to provide better resolution at the sub-watershed level and to streamline the data updating process – automating the web-downloading process from public agency websites. This has been accomplished for surface flow and water quality data from the California Data Exchange website (CDEC), crop evapotranspiration data from the California Irrigation Management Information System (CIMIS) and for certain climatic data from the National Oceanic and Atmospheric Administration (NOAA). The model has been further customized with a new "Manager Module" to simplify running simulations and forecasts through the Model User Interface and make more accessible customized visual outputs of the model to enhance decision support capabilities.

6. Bibliography

American Society of Civil Engineers– Environmental and Water Resources Institute. 2014. Draft report of models used for TMDL analysis. TMDL Working Group, 2014.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle Jr., T.H. Jobes, A.S. Donigian, Jr. (2005), *HSPF Version 12.2. User's Manual*, AQUA TERRA Consultants in Cooperation with U.S. Geological Survey and U.S. Environmental Protection Agency.

Binger, R.L., F.D. Theurer and Y. Yuan (2011), *AnnAGNPS Technical Processes; Documentation Version 5.2*, U.S. Department of Agriculture.

Bo Zhang, Yu Qin, Mingxiang Huang, Qiang Sun, Shun Li, Liqiang Wang, Chaohui Yu. 2011. SD–GIS-based temporal–spatial simulation of water quality in sudden water pollution accidents *Computers & Geosciences*, *Volume 37, Issue 7*, *July 2011*, *Pages 874-882*

Bottcher, D. and J.G. Hiscock. *WAMView – A GIS/Land Source Based Approach to Watershed Assessment Model.*

Chen, C.W., 1970. "Concepts and Utilities of Ecologic Model", Journal of Sanitary Engineering Division, ASCE, Vol. 96, No SA5, pp. 1085-1907.

Chen, C.W. and G.T. Orlob. 1975. "Ecologic Simulation for Aquatic Environments", in Systems Analysis and Simulation in Ecology, Vol. III, B.C. Patten, Editor, Academic Press, New York, NY. pp 475-588.

Chen, C.W., J.D. Dean, S.A. Gherini, and R.A. Goldstein, 1982 "Acid Rain Model - Hydrologic Module". Journal of Environmental Engineering, ASCE, Vol 108, EE3: 455-472.

C.W. Chen, J. Herr, R.A. Goldstein, F.J. Sagona, K.E. Rylant, and G.W. Hauser, 1996. "Watershed Risk Analysis Model for TVA's Holston River Basin." *Water, Soil, and Air Pollution*, Vol. 90, pp. 65-70.

Downer, C.W., and F.L. Ogden, 2004, GSSHA: A model for simulating diverse streamflow generating processes, *J. Hydrol. Engrg.*, 9(3):161-174.

EPRI (2001), *Watershed Analysis Risk Management Framework: Update One: A Decision Support System for Watershed Analysis and Total Maximum Daily Load Calculation, Allocation and Implementation,* Palo Alto, CA. 1005181.

Fotheringham, A.S., J.P. Wilson. 2007. Geographic Information Science: An Introduction. In Wilson, J.P., Fotheringham, S.A. (eds) Handbook of Geographic Information Science. Oxford: Blackwell, pp. 1-10.

Gassman, P.W., J.R. Williams, X. Wang, A. Saleh, E. Osei, L.M. Hauck, R.C. Izaurralde and J.D. Flowers (2009), *The Agricultural Policy Environmental EXtender (APEX) Model: An Emerging Tool for Landscape and Watershed Environmental Analyses*, Center for Agricultural and Rural Development, Iowa State University. Technical Report 09-TR 49.

Graham W.D. , A. S. Donigian Jr., R. Munoz-Carpena, W. Skaggs and A. Shirmohammadi (2009), *Peer Review of the Watershed Assessment Model (WAM). http://waterinstitute.ufl.edu/news/downloads/WAM_final_report.pdf*.

Innovyze, 2013. QualWatch, Next Generation of Early Warning Network Monitoring and Water Quality Event Detection: http://www.innovyze.com/products/qualwatch/

Jiang J., P. Wang, W. Lung, L. Guo, M. Li. A GIS-based generic real-time risk assessment framework and decision tools for chemical spills in the river basin Journal of Hazardous Materials, Volumes 227–228, 15 August 2012, Pages 280-291

Kulawiak M., A. Prospathopoulos, L. Perivoliotis, M. łuba, S. Kioroglou, A. Stepnowski. 2010. Interactive visualization of marine pollution monitoring and forecasting data via a Web-based GIS *Computers & Geosciences*, *Volume 36, Issue 8*, *August 2010*, *Pages 1069-1080*.

Neitsch, S.I., J.G. Arnold, J.R. Kiniry, J.R. Williams (2011), *Soil & Water Assessment Tool, Theoretical Documentation, Version 2009,* Texas Water Resources Institute, College Station, TX. Technical Report No. 406.

Ng S.M.Y, O.W.H. Wai, Y-S Li, Z-L Li, Y. Jiang. 2009. Integration of a GIS and a complex three-dimensional hydrodynamic, sediment and heavy metal transport numerical model *Advances in Engineering Software*, *Volume 40, Issue 6*, *June 2009*, *Pages 391-401*.

Rossman L.A. (2010), *Storm Water Management Model, User's Manual, Version 5.0*, U.S. Environmental Protection Agency, Cincinnati, OH. EPA/600/R-05/040.

Tetra Tech, Inc. *The LSPC Watershed Modeling System; User's Manual,* U.S. Environmental Protection Agency.

Texas A&M, *APEX – Agriculture Policy/Environmental eXtender Model,* http://epicapex.tamu.edu/apex/.

U.S. Department of Agriculture (USDA) (2014), *Watershed-Scale Pollutant Loading Model – AnnAGNPS v5.4: Fact Sheet.*

U.S. Environmental Protection Agency (EPA), 2007. Real-Time Internet Visualization and Environmental Reporting Network (RiverNet): the Upper Susquehanna/Lackawanna American Heritage River: http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/419)

U.S. Environmental Protection Agency (EPA), *Loading Simulation Program in C++ (LSPC) Fact Sheet*. http://www.epa.gov/athens/wwqtsc/html/lspc.html.

U.S. Environmental Protection Agency (EPA), *Storm Water Management Model, Fact Sheet*. http://www.epa.gov/athens/wwqtsc/html/swmm.html

U.S. Environmental Protection Agency (EPA), *Watershed Assessment Model (WAMView), Fact Sheet*. http://www.epa.gov/athens/wwqtsc/html/wamview.html.

U.S. Environmental Protection Agency (EPA), *Loading Simulation Program in C++ (LSPC) Fact Sheet*. http://www.epa.gov/athens/wwqtsc/html/lspc.html.

Velasco V., I. Tubau, E. Vázquez-Suñè, R. Gogu, D. Gaitanaru, M. Alcaraz, A. Serrano-Juan, D. Fernàndez-Garcia, T. Garrido, J. Fraile, X. Sanchez-Vila GIS-based hydrogeochemical analysis tools (Quimet). Computers & Geosciences. 8 May 2014.

APPENDIX A : Summary comparison of features of water quality models most alike the current WARMF-SJR model in functionality.

Category	Metric	WARMF	AnnAGNPS	APEX	GSSHA	LSPC/HSPF
Surface Water	Approach to SW Flow	Precipitation and groundwater accretions to streamflow are calculated and then flow is routed between sub basins using the kinematic wave equation. User must specify a stage width curve for each segment.	Runoff quantities based on runoff curve numbers. Hydrology model is based on water balance. Flow in river reaches is calculated using the kinematic wave and Manning's equations.	Flow through channels, reservoirs and floodplains simulated using variable storage coefficients and Muskingum methods. Surface runoff is based on either runoff curves or the Green and Ampt equation. Flow routing can be computed on either a daily basis or a short time interval for flood routing.	2-D overland flow, 1-D streamflow generated from spatially and temporally varying precipitation. Overland flow based using diffusive wave. Chanel network is described with links and nodes that are associated with grid cells.	Flow is simulated using modules from HSPF. Assumes completely mixed reaches, unidirectional flow and flow routing with kinematic wave. Uses a function table for depth discharge relationships.
	Lakes and Reservoirs	Yes - reservoirs are simulated through a link with CE-QUAL-W2	! Not really - There are impoundments for sediment control but no reservoirs.	Yes	Yes - The model simulated lake storage and routing using level pool routing.	Yes
	Wetlands	No	No	No	* Yes - the model can simulate wetland and peat layer hydraulics using mixed Darcian and manning's flow	Not discussed
Groundwater	Approach to GW Flow	Dynamic water balance- physically based	Soil moisture balance simulated for two soil layers but there is no groundwater	Mainly focused on soil moisture balance. It can simulate fluctuations in groundwater depth, but there are no direct links between water table calculations and other hydrologic processes.	1-D infiltration and 2-D groundwater flow. Full coupling between groundwater, shallow soils, streams and overland flow.	Flow is simulated using modules from HSPF. In HSPF Water infiltrates from the surface and can be stored in 'active groundwater storage' or percolate to deep groundwater.
	Flow to River	There can be exchanges between surface water and the unsaturated zones of soil layers	Not directly, but runoff does increase with increasing soil moisture	Yes	Stream aquifer interactions and exfiltration based on Darcy's Law	Yes- active groundwater storage can reappear in the river as baseflow
	Deep percolation	Does not model deep groundwater aquifers below 4 soil layers	There are losses from soil moisture but no groundwater	Yes -Infiltrated water can be stored in the soil profile, percolated to groundwater, lost to ET or routed laterally to subsurface or tile drain flow.	1-D infiltration based on Green & Ampt or 1D vertical Richard's	Yes
	Lateral GW flow	Does not model deep groundwater aquifers below 4 soil layers, but there is lateral flow in the soil layers using the Darcy equation	Lateral flow in the soil is calculated using Darcy equation but there are no deep layers	Lateral soil moisture flow but no groundwater simulation	* 2-D vertically averaged saturated flow and 1-D Richards equation in the Vadose zone	Yes - Groundwater flow and loss is simulated for the active groundwater zone.
Land Surface	ET	PET is calculated using meteorological variables and the Hargreaves equation. Actual ET is determined based on water availability.	FAO ET and crop component guidelines combined with PET calculations based on meteorological variables	Five different PET options are available. Evaporation is computed for soils and plants separately.	Yes- Modeled using Deardorff Penman-Monteith equation with seasonal canopy resistance	Yes - Calculated using HSPF. First, PET is calculated and this value is adjusted based on water availability in the surface and subsurface.
	Snow processes	Yes snow melt and accumulation are physically based.	Yes	Yes	Yes - Based on energy balance	Yes - Snowfall and melt are included in water budget
	Land Cover	There are many built in options and you can add your own. The user can specify multiple land cover types in a catchment.	Crop growth stages are included by land cover type	* Yes - Includes many options(~100 different crops) and is able to simulate dynamic crop growth	Spatially variable land cover by grid cell	Each sub watershed is represented by multiple land units based on land use coverages (land use can be pervious or impervious)
	Erosion	Yes	Yes- Using RUSLE	Yes	Yes- Includes processes for overland erosion, channel sediment transport and sediment in lakes.	Yes
Water Management	Drains	No	* Yes	* Yes	Tile drains can be simulated using grid pipes.	No
	Irrigation	User specifies the application rate and the flow source for each catchment	Yes - includes many irrigation options (e.g. spray, furrow, drip). Can also do automatic irrigation scheduling based on soil moisture.	* Irrigation can be manual (scheduled by date and volume) or automatic (triggered by water stress).	! No irrigation capabilities listed	! Not discussed
	Surface water Diversions	Yes - The user specifies water sources when they irrigation is defined. Time series of diversions are provided for river reaches.	! No	Yes - Can divert water from streams or reservoirs and transfer water from one stream or reservoir to another.	Diversions can be specified using depth discharge rating curves or specified discharges.	! Not discussed
	Groundwater Pumping	No	No	* Yes - The user can specify for water to be taken from the aquifer.	Yes - Wells can have dynamic or static pumping rates	Not discussed
	Fertilizer	Yes - The user specifies the application rate per hectare for each month and land use type	Yes	Yes	! No	! No

Category	Metric	WARMF	AnnAGNPS	APEX	GSSHA	LSPC/HSPF
	BMPs	The primary BMP options built into the model are: livestock fencing, street sweeping, buffer zones, detention ponds, and changes in tillage.	They mention BMPs in the model summary but there are not many details in the technical documentation about how these would be implemented.	* Can simulate many different land management practices like changes in irrigation methods, drainage, furrow diking, buffer strips, terraces, fertilization, manure management lagoons, changes in tillage	BMPs are not included automatically but it can simulate many BMPs by adjusting input parameters and there are example applications that simulate BMPs	! User can specify load reduction for point and nonpoint sources.
Water Quality	**General Approach to WQ modeling**	Physically based geochemistry and mass balance, includes adsorption. Within each model element WARMF assumes a Continuously Stirred Tank Reactor (CSTR) model.	Chemicals are either dissolved or adsorbed to particles. In both cases routing is based on conservation of mass. Soluble nutrients are partitioned between surface runoff and infiltration. Loadings can be identified at their source and tracked through watershed.	Physically based and encompassing many processes such as; leaching, surface runoff subsurface flow, volatilization, mineralization, immobilization and partitioning between solution and sediment phases.	User can specify how to model water quality, simple constituents or full nutrient cycle. There is an option to simulate exchange with soil and contaminant removal through infiltration.	Simulates water quality in stream using advection and decay processes. Also includes accumulation and wash off from land surfaces
	Temperature	Yes	Yes	Yes	! Not discussed	Yes
	Constituents	Many - Including nutrients, salinity, BOD, pathogens, suspended sediment, pesticides and metals	! Sediment, nitrogen, phosphorus, and pesticides	Simulated carbon cycling, nitrogen cycling, phosphorus cycling and pesticides. Doesn't include salinity.	Many	Many, however salinity is not mentioned.
	Atmospheric Deposition (other than rainfall concentration)	Yes	! No	! No	! No	No
	TMDL Calculations	Built-in module for TMDL calculations	! Not automatically, but results could be used to determine TMDLS	! Not directly but you could use it for this	! No	Yes - It has a separate module for TMDL calculations
	Point and non-point sources	Yes	Yes	Designed for non-point source agriculture, but it can include point sources too.	Yes - user specifies time varying mass or concentration inputs.	Yes
Model Structure	**Lumped or gridded**	Lumped by sub-watersheds - WARMF divides the basin into land catchments, river segments and stacked reservoir layers	Watershed is divided into homogeneous land areas that can be any shape including square grids	Basin is divided into subareas	Gridded	Lumped by sub watershed
	Ability to subdivide basins into sub watersheds	Yes	Yes using the TOPAZ input generator	Yes	WMS can be used to delineate watersheds	Yes - Using the WCS extension for model setup
	Typical spatial resolution	Catchment size is flexible but usually its roughly 11 digit HUC size	Not reported	Not documented	Can be used for large watersheds	Not listed
	Typical spatial extent	Good for big basins. Demonstrated up to 16,000 sq. miles	Can be used for 'very large' watersheds	Not specifically documented but it says It's applicable to large basins	Varies by application, has been used for high resolution urban simulations and lower resolution regional simulations.	Designed for large-scale watersheds, can handle systems with over 1,000 sub watersheds
	Typical time steps	Daily dynamic simulation	Daily dynamic simulation	Daily time step and has been used to simulate hundreds of years	Time steps can vary but hourly inputs are common	Hourly or daily
Input and Output	**Input database included**	Doesn't come with an input database but its noted that the model can be primarily populated with publically available datasets	Can import RUSLE soil erosion databases directly	Doesn't come with any input database	No	* Yes - Model data is automatically extracted from the underlying Access database
	Pre-processing tools	Can use BASINS to setup a WARMF model	Domains created using GIS-assisted computer program (TOPAZ). There is also an input editor to export, initialize, complete and/or revise input data. Now there are options to import and export in CSV format so that datasets can be developed using spreadsheets.	No pre-processing tools directly in the model but ArcAPEX appears to be a GUI for inputs	GSSHA has been coupled with WMS to help with domain setup	Its part of the TMDL toolbox and you can used the WCS extension for model setup
	GUI/ visualization tool	GIS based GUI (no ArcView required once model is setup)	Integrated GIS interface.	There is and ArcGIS-ArcView extension for APEX	Outputs can be viewed in WMS	It has a GIS interface and has outputs compatible with ArcView shape files. Also, through this interface there is a control center for launching scenarios.
	Ability to automatically incorporate real time data	Not automatically, but you can update simulations with new data.	No	No	No	No

Category	Metric	WARMF	AnnAGNPS	APEX	GSSHA	LSPC/HSPF
Input and Output	**Ability to Retrieve hydrologic data from database or web server**	It does not do this automatically. Users must follow several steps to import new data manually.	Not automatically	No	No	No
Input and Output	**Output format and DB interactions**	Does include output database and outputs are linked to GIS.	There is an output processor that generates a summary of results in tabular or GIS format	Output files have a standardized format but there isn't a post processor directly incorporated into the model. Possibly ArcAPEX could be used for post processing.	Outputs are formatted to interact with WMS	Uses a Microsoft Access database to manage model data
Input and Output	**Ability to view time series**	Yes	Yes for predefined points	There are time series outputs	Gridded time series are output for many variables. Time series of discharge and depth can be produced at any node in the channel	Yes can express outputs or hourly daily and there is an analysis tool
Input and Output	**Ability to view results by watershed and by reach**	Yes	Yes: Outputs are expressed on an event basis for selected stream reaches and source tracking	Results are spatially distributed	Yes all of the results are spatially distributed	Yes - Outputs are generated by sub watershed for all land-layers, reaches and simulated modules
Source Code	**Publically available**	Model is free but applications are proprietary.	Yes	Model is Free	Yes	Yes
Source Code	**Language**	Fortran	Fortran	Fortran	C	C++
Source Code	**Actively used**	Yes	Yes	Yes	Yes	Yes -Its part of the EPA TMDL toolbox
Limitations		No groundwater or agricultural drains	1. All runoff and loading for a single daily event are routed to outlet before next day simulation 2. No tracking of nutrients and pesticides on sediment deposited in the stream from one event to next 3. Point sources are limited to constant loading rates for entire simulation period 4. Limited water quality constituents and no salinity	Limited water quality constituents, no salinity and no TMDL Calculations	Does not appear to be well suited for agricultural simulations. No mention of irrigation or fertilizer application.	Does not appear to have the same land management capabilities as WARFM and there is no discussion of irrigation practices or fertilizer application
Overall Comparison to WARMF			Similar groundwater capabilities (with the addition of tile drains) and general approach, but does not have the ability to handle as many constituents (e.g. no salinity). Also it does not do automated TMDL calculations. Overall does not have many significant advantages over WARMF. Technical documentation indicates a focus on erosion processes.	APEX has some advantages over WARMF. It appears to have better groundwater simulation capabilities and more land cover types with dynamic crop growth and the option to do moisture dependent irrigation. It also has a wide array of land management techniques and there are many options to simulate managed grazing. However, it does not have a TMDL module and there is no GUI other than the download ArcGIS tool. Also it doesn't handle as many water quality constituents as WARMF and it doesn't do salinity.	GSSHA is a physically based gridded model that has some advantages over WARMF with respect to groundwater and wetland processes. However, it seems to be designed more as a hydrologic model than a water quality model. It does not include irrigation and fertilization and is not designed to calculate TMDLS.	LSPC appears to compare quite closely with WARMF. It has a built in TMDL module and is designed to analyze point and non-point source loading. It doesn't have as many built in land management features but it is part of the EPA TMDL toolbox and has pre and post processing tools and a GIS interface.

Category	Metric	SWAT	SWMM	WAMview
Surface Water	Approach to SW Flow	Physically based overland flow divided into land phase and routing phase. Runoff volume can be calculated using SCS curve number procedure or Green &Ampt Infiltration method. Routing is based on Muskingum method and includes transmission and evaporative losses as well as bank storage.	! Conceptualizes the system as a network of nodes and links consisting of conveyance, storage and treatment units that transport water. Inputs to transport network come from surface runoff, interflow dry weather flow or hydrographs. Flow in conduits is modeled using Manning's equation and kinematic or dynamic wave routing	Dynamic flow routing using Manning's equation. Flow attenuation is based on flow rate, flow path, and distance traveled.
	Lakes and Reservoirs	Yes - Considers changes in storage volume as well as losses to evaporation and seepage	Yes, but they are just storage buckets (i.e. not physically based).	Yes
	Wetlands	* Yes	No	* Yes there is a sub-model for wetlands
Groundwater	Approach to GW Flow	Physically based. Simulates multiple layers. Top two meters are soil molded with kinematic storage model. Below the soil there are two aquifer systems, the shallow unconfined aquifer and the deep confined aquifer	Groundwater is a compartment in the model. It receives infiltration from the land surface and transfers part of this inflow to the transport compartment as interflow. Aquifers are modeled using Aquifer objects.	Cell to stream routing of overland and groundwater flow; Boussinesq equation for shallow saturated groundwater flow
	Flow to River	Yes -There includes interflow to the river from lateral flow in top 2 meters and base flow from the shallow or deep aquifers.	Yes - Interflow between groundwater and drainage system	No exfiltration of groundwater to the surface
	Deep percolation	* Yes - There is an upper soil layer and deeper aquifer layers. Initial infiltration depends on soil moisture. Water that percolates past the root zone is partitioned into the two aquifers.	Yes - Water infiltrates to the groundwater using either Horton, Green-Ampt or curve number infiltration.	Yes - There is infiltration but no re-infiltration of runoff once it is generated.
	Lateral GW flow	* Lateral subsurface flow is calculated with redistribution for the top 2 meters using a kinematic storage model.	No - There are aquifer elements that account for groundwater surface water exchanges, but its all vertical.	No- Does not allow for dynamic groundwater flow paths that vary with hydrologic conditions.
Land Surface	ET	Potential evapotranspiration is calculated with Penman Monteith, Priestly-Taylor or Hargreaves equations. Actual ET is adjusted from PET and accounts for interception as well as bare soil sublimation and evaporation	! Evaporation is calculated from standing water on the land surface or water in storage. There is no transpiration. Users can input a single value, monthly values or a time series for evaporation rates.	Yes - Different field scale models are selected depending on the land use types and cell combinations.
	Snow processes	Yes	Yes	Not discussed
	Land Cover	Many plant and crop types and it accounts for seasonal growth cycles	User defined land 'uses' rather than land 'cover'. Examples include, residential, commercial, industrial and undeveloped. Not many natural or agricultural choices	There are many urban and rural land use choices. Land use is spatially variable and can be changed through ArcView for different scenarios.
	Erosion	Yes	! No	Yes
Water Management	Drains	Yes	Yes - Underdrain systems can be modeled as a series of slotted pipes	Yes- Can simulate artificial drainage
	Irrigation	Yes - Irrigation can be applied manually or automatically	! No	! Not Discussed
	Surface water Diversions	Yes	Yes you can setup diversions in the network structure.	Yes
	Groundwater Pumping	* Yes	No	No
	Fertilizer	Yes - User can specify automatic or continuous application. Pesticides can also be applied.	! No	! Not Discussed

Category	Metric	SWAT	SWMM	WAMview
	BMPs	Yes - SWAT has the ability to simulate a broad array of management practices. For example timing of tillage, fertilizer application and irrigation rates can be changed. Also, BMP installments like filter strips can be simulated.	Runoff reduction can be simulated using Low Impact Developments (LIDs), but these mostly relate to urban management not agricultural	Yes - For example, it can incorporate stormwater treatment areas and reservoir assisted stormwater treatment areas
Water Quality	General Approach to WQ modeling	Physically based. Includes the movement, degradation and transformation of many constituents. Special focus on agricultural constituents like nutrients, pesticides and algal growth.	SWMM can simulate transport and buildup of many constituents. User specifies, concentration in rainfall, groundwater, inflow, dry weather flow and first order decay coefficients. User can also specify co-pollutants. Build up and wash off is determined by land use. Conduits are treated as continuously stirred tank reactors.	Water quality can be modeled using spatial assessment using impact indices or detailed hydrologic and contaminant transport modeling. Approach depends on the constituents of interest.
	Temperature	Yes	! No	! No
	Constituents	Many - Including: nutrients, pesticides and bacteria in addition to BOD and DO	Many - User defines decay coefficients and input concentrations	Soluble phosphorus, particulate and soluble nitrogen, total suspended solids and BOD. Also it has been linked to WASP to simulate dissolved oxygen and chlorophyll A.
	Atmospheric Deposition (other than rainfall concentration)	* Yes both wet and dry deposition	! No	! No
	TMDL Calculations	! No - could be used for this but there is no automated module	! No - Its part of the EPA toolbox but doesn't include an explicit TMDL module	Yes - Has been used for phosphorus load allocations
	Point and non-point sources	Yes	Yes	No
Model Structure	Lumped or gridded	Lumped by sub basin and input information and further grouped by hydrologic response units	Lumped by sub catchment and modeled as a network of nodes and links.	Gridded
	Ability to subdivide basins into sub watersheds	Yes - this can be done using the BASINS system	! User is responsible for defining sub catchments and outlet points	The gridded approach does not rely on sub basins but they can still be determined with ArcView
	Typical spatial resolution	Not listed	Not listed	Recommended grid size of 1 hectare for watersheds of 26,000 square km or larger
	Typical spatial extent	Not listed, but has been applied to large regional problems	Designed for regional systems.	WAM has been applied to watersheds that extend thousands of kilometers
	Typical time steps	Weather generation is on a daily time step, but you can do sub daily. Continuous time model designed for long term simulations not single event flood routing.	Can have different time steps for different processes. Time steps vary but hourly is demonstrated.	Examples presented were hourly, but outputs can be annual daily or hourly.
Input and Output	Input database included	SWAT is part of the BASINS system which has a GIS database and web data download tool.	No	* Yes - Map coverages are included with the model
	Pre-processing tools	Yes - Through BASINS	No - The GUI helps the user define their system but sub catchments and drainage points must be determined beforehand.	The ArcView interface allows the user to create and modify scenarios in GIS.
	GUI/ visualization tool	User interfaces have been developed in Windows, Grass and ArcView	SWMM has a GUI that allows users to setup the system with visual objects that are mapped in the SWMM workspace	WAMView has a model interface written in ArcView
	Ability to automatically incorporate real time data	No	No	No

Category	Metric	SWAT	SWMM	WAMview
Input and Output	Ability to Retrieve hydrologic data from database or web server	* Yes - BASISN has a data download tool that downloads data and imports to GIS.	No	No
	Output format and DB interactions	Many outputs are generated for various aspects of the system.	All outputs are generated in a binary file	Outputs are formatted to interact with ArcView.
	Ability to view time series	Not directly with SWAT but there are post processing tools like SWATPlot and SWATGraph that can do this.	The GUI can create time series plots and tables, profile plots and perform statistical analysis.	Yes - There are time-series outputs at the source cells, sub basins and individual reaches including loading and attenuation
	Ability to view results by watershed and by reach	Yes spatially distributed outputs are generated.	Yes with the GUI you can look at specific locations	Yes - Can view results by grid cell, sub basin or stream reach
Source Code	Publically available	Yes - and the BASINS GIS interface is also open source	Yes	Yes, but you will need ArcView
	Language		C	Interface in ArcView
	Actively used	Yes - its part of the EPA BASINS tool	Yes - Its part of the EPA TMDL toolbox	Yes - Has been applied to several watersheds
Limitations		The biggest limitation for SWAT as a stand alone model are its visualization capabilities. However, this is largely overcome through tools like SWATPlot and its incorporation into the BASINS system.	There are two major limitations to the SWMM model. First, it was primarily designed for urban stormwater runoff so it doesn't have many agricultural options. Second, it is very parameterized and is less physically based than some of the other watershed tools.	WAMView is generally physically based, but there are also many parts that are highly parameterized. For example, it has a simplified approach for cell-to-stream water and solute delivery. Also, documentation is limited so its difficult to see exactly what its doing in many instances.
Overall Comparis		SWAT was developed to quantify the impact of land management practices in large, complex watersheds. It has many of the same capabilities as WARMF and usually a physically based approach. Its primary advantages over WARMF are its groundwater capabilities.	SWMM was primarily designed for stormwater runoff from urban areas but it can do long-term continuous simulations too. It is less sophisticated than WARMF with respect to physical processes and non-urban environments. However, its main advantage is the GUI that allows users to setup domains using visual objects and to post process results easily from the same interface.	Grid-based watershed simulation model especially applicable to areas with groundwater flow. Strengths are its GIS foundation, spatial detail and process-based field-scale modules.

Key
! = Capability that is present in WARMF but not in the model being considered
* = Capability of the model being considered that is not available in WARMF