Using the Climate Assessment Tool (CAT) in U.S. EPA BASINS Integrated Modeling System to Assess Watershed Vulnerability to Climate Change

J.C. Imhoff*, J.L. Kittle, Jr.**, M.R. Gray***, and T.E. Johnson****

* AQUA TERRA Consultants, P.O. Box 323, Ouray, CO 81427
(E-mail: *jcimhoff@aquaterra.com*)
** AQUA TERRA Consultants, 150 E. Ponce de Leon Ave., Suite 355, Decatur, GA 30030
(E-mail: *jlkittle@aquaterra.com*)
*** AQUA TERRA Consultants, 150 E. Ponce de Leon Ave., Suite 355, Decatur, GA 30030
(E-mail: *markgray@aquaterra.com*)
**** U.S. EPA Global Change Research Program, 1200 Pennsylvania Ave., NW Washington, DC 20460
(E-mail: *johnson.thomas@epa.gov*)

Abstract

During the last century, much of the United States experienced warming temperatures and changes in amount and intensity of precipitation. Changes in future climate conditions present additional risk to water and watershed managers. The most recent release of U.S. EPA's BASINS watershed modeling system includes a Climate Assessment Tool (CAT) that provides new capabilities for assessing impacts of climate change on water resources. The BASINS CAT provides users with the ability to modify historical climate and conduct systematic sensitivity analyses of specific hydrologic and water quality endpoints to changes in climate using the BASINS models (Hydrologic Simulation Program – FORTRAN (HSPF)). These capabilities are well suited for addressing questions about the potential impacts of climate change on key hydrologic and water quality goals using the watershed scale at which most important planning decisions are made.

This paper discusses the concepts that motivated the CAT development effort; the resulting capabilities incorporated into BASINS CAT; and the opportunities that result from integrating climate assessment capabilities into a comprehensive watershed water quality modeling system.

Keywords

BASINS CAT; climate assessment; climate impact; HSPF; integrated watershed modeling

INTRODUCTION

The most versatile tool available for evaluating the relationships between dynamic environmental stressors, various watershed endpoint responses and necessary watershed management practices is a watershed modeling *system* that includes a suite of models and support tools as well as a full repository of environmental data (Fitzpatrick et al., 2001). The variety of management issues facing watershed managers requires that the watershed model(s) be dynamic and comprehensive in nature. During the past decade, intensive collaborative efforts between academicians, engineers and public agencies have developed a small number of effective and widely used watershed modeling systems. In the United States, one of the most commonly used modeling systems is the U.S. Environmental Protection Agency's *Better Assessment Science Integrating Point and Nonpoint Sources* (BASINS) (USEPA, 2007).

Managing the risk associated with environmental variability has long been a principal focus of watershed management. Perhaps paramount among environmental variability is consideration of climate. Management plans are developed, and water infrastructure is designed and operated to be resilient to anticipated variability in climate. In most areas, however, estimates of future conditions are made assuming that near-term and long-term climate patterns are stationary, and thus that future conditions can be represented by observed variability over some relatively short period within the

20th Century. This assumption contradicts the conclusions of extensive ongoing climate research (IPPC, 2001).

Water and watershed systems are influenced by the amount, form, seasonality, and event characteristics of precipitation, as well as temperature, solar radiation and wind that affect evaporative loss. Ultimately, these changes may be reflected in key management targets, such as Total Maximum Daily Loads (TMDLs), duration flow events (e.g., seven-day, consecutive low flow with a ten year return frequency or 7Q10), maximum water temperatures, or nutrient loads. System vulnerability, or susceptibility to harm, is determined by the sensitivity inherent in the cause-effect relationships between weather changes and various watershed endpoints. Changing weather selectively affects each of a collection of management practices that are planned or implemented within a watershed, with the possibility of producing either beneficial or adverse effects on individual management practices.

To reduce the likelihood of future adverse impacts, watershed managers must be able to assess potential risks and opportunities, and where appropriate, implement practices for adapting to future climatic conditions. Current climate models have a limited ability to predict climate at the local and regional scales needed by managers. Accurate predictions of future climate, however, should not be considered a necessary precursor to developing and implementing watershed-scale actions in response to climate change (Sarewitz et al., 2000). Even with uncertainty in predictions, managers can effectively manage risk by implementing practices and strategies that make systems robust to a wide range of plausible future conditions and events (Pielke and de Guenni, 2004).

The development effort reported in this paper resulted from the need to provide tools and information to help water managers understand and manage the potential impacts of climate change on water resources at the watershed scale. This required a flexible approach for developing climate change scenarios, coupled with a robust watershed modeling system. Doing so enables a previously unavailable capability to link climate change and variability to watershed response. The USEPA's BASINS modeling system (USEPA, 2007) was selected as the framework for achieving this integration.

METHODS

BASINS CAT provides a robust set of capabilities for representing and exploring climate change and its relationship to watershed science. The development effort has resulted in integration of new tools into BASINS that allow the user to create weather scenarios for assessing climate change impacts on endpoints useful for watershed management.

BASINS

BASINS provides a GIS-based framework to evaluate watersheds throughout the United States. BASINS was originally developed to support the TMDL requirement of the United States' Clean Water Act, and has further established itself as an effective tool for performing many other types of watershed assessments. The BASINS system combines five components to provide the range of applications needed for performing watershed and water quality analyses: 1) a comprehensive collection of national cartographic and environmental databases, 2) environmental assessment tools (to summarize results; establish pollutant source-impact interrelationships; and selectively retrieve data); 3) utilities (e.g., import tool, download tool, grid projector, post-processor, and land use, soil classification and overlay tool); 4) automated watershed characterization reports (for eight different data types); and 5) models including HSPF (Bicknell et al., 2005), AQUATOX (Clough and Park, 2006), SWAT (Arnold and Fohrer, 2005), AGWA (Burns et al., 2004) and PLOAD-BEHI (USEPA, 2007).

The software design of BASINS is based on a set of interoperable components. Each component performs specific tasks such as data download, time series visualization or map projection. Existing BASINS tools used to summarize and compare modeling results have been refactored to provide additional capabilities and flexibility needed to support the Climate Assessment Tool.

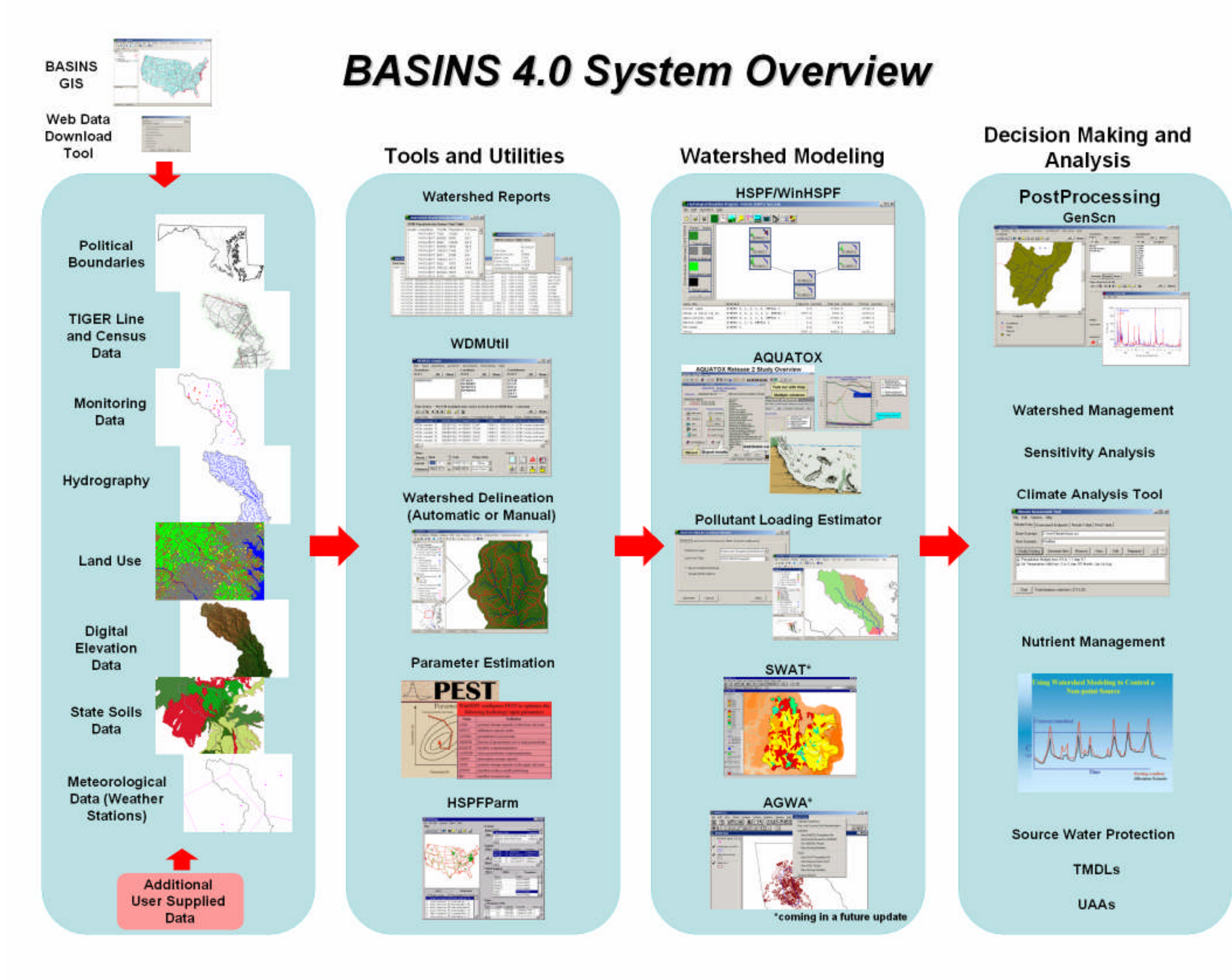

Figure 1. U.S. EPA BASINS Integrated Modeling System

Climate Assessment Tool (CAT)

CAT has been implemented as a component of the development effort that created Version 4.0 (Figure 1) of the BASINS modeling system. CAT provides BASINS users with a flexible approach to modify historical weather time series and use these data as the meteorological input to the Hydrological Simulation Program – FORTRAN (HSPF) watershed model (Bicknell et al., 2005).

Specific capabilities of CAT currently focus on an ability to create and run new meteorological time series that are created by modifying historical data. Users can modify historical data using standard arithmetic operators applied monthly, seasonally or over any other increment of time. Increases or decreases in a climate variable (precipitation, air temperature) can be applied uniformly, or they can be selectively imposed on only those historical events that exceed (or fall below) a specified magnitude. This capability allows changes to be imposed only on events within user-defined size classes, and can be used to represent the projected effects of ‘intensification’ of the hydrologic cycle, whereby larger precipitation events intensify, instead of events becoming more frequent. In addition, users are able to create time series that contain more frequent precipitation events. With these capabilities, users have the ability to represent and evaluate a wide range of potential future climatic conditions and events including future climate projections, historical events, or re-combinations of historical events.

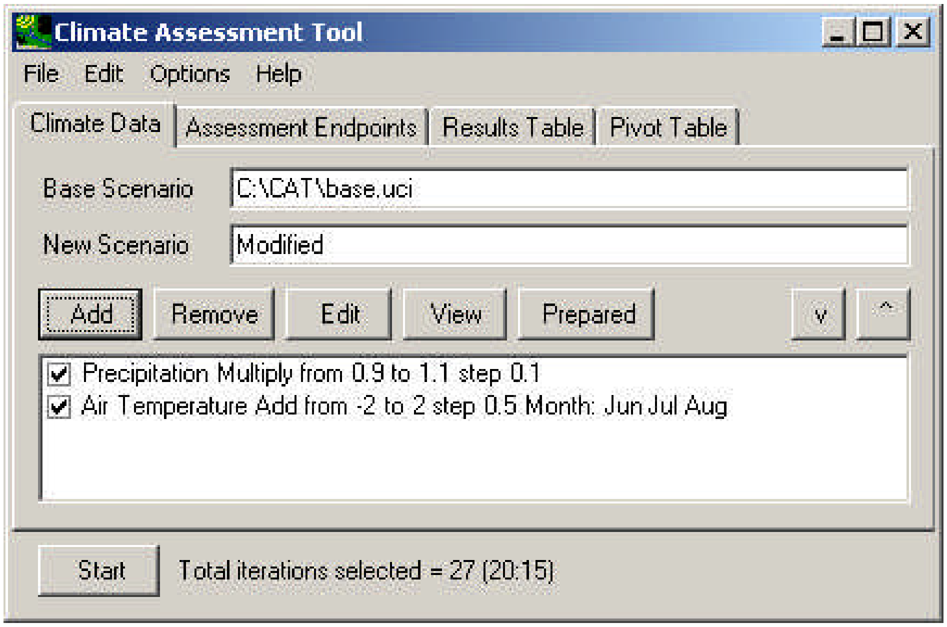

Figure 2. Example Interaction Tab for BASINS CAT.

Figure 2 provides an example of the user interaction environment for CAT. The 'Climate Data' tab that is shown contains a list of the climate data which will be used as inputs to the hydrologic simulation. Climate data may either be prepared outside CAT and then located using the 'Prepared' button or, as pictured here, may be specified as modifications of existing climate data. In this example, precipitation will be varied from 90% to 110% of historical values, and air temperature will be varied by plus or minus two degrees during summer months. Other CAT windows enable wide flexibility when choosing how to modify historic data and when choosing endpoints to measure the effects of the changes. Seasonal differences can be created and measured, precipitation can be selectively modified during storm events if desired, and many statistics can be computed from the model results.

Single Scenario Assessment

CAT users can assess the impact(s) of climate change scenarios on targeted endpoints under current watershed land conditions; additionally, they can investigate climate change-induced alterations in the effectiveness (improved or diminished) of in-place or planned management practices. It is intuitive that certain watershed land uses are more vulnerable to climate change than others. The HSPF watershed model allows users to develop watershed models that represent an extensive mix of land uses (and management practices) and a robust list of hydrologic, chemical and biological processes and endpoints. The watershed impacts of climate change can thus be assessed in a comprehensive manner, while at the same time individual applications are directed at specific endpoints. Further, endpoint impacts can be examined at various levels of spatial, temporal and process detail as needed to achieve the objectives of a specific investigation.

Sensitivity Assessment

CAT users can also automate model runs to conduct systematic sensitivity analyses of specified hydrologic and water quality endpoints to a range of climatic changes. In this mode, the user provides the type and range of climatic variability to be considered. The tool then creates and manages the meteorological inputs, runs the watershed model (hydrology and water quality), manages model output, and provides tabular summaries of the response of selected endpoints. A post-processing capability has also been developed that calculates numerous endpoint metrics such as x-year, y-duration high or low flow event, annual water yields, and annual pollutant loads. This post-processing capability allows and greatly facilitates sensitivity assessments to be conducted for key management targets (Johnson and Kittle, 2006). Water and watershed managers are able to assess the impacts of climate change in terms of the metrics that are traditionally used for understanding impacts and making decisions within their specific professions or management domains.

RESULTS AND DISCUSSION

Single Scenario Assessment

Table 1 shows results from an example application of CAT to perform an assessment of pollutant loadings in response to changes in precipitation and air temperature. The table displays total nitrogen loading (kilograms) for each of twenty land use types in the 1900 km^2 Monocacy River, Maryland watershed for base conditions and based on a climate change projection for the period of 2010-2039 from a climate modeling experiment using the ECHM (German High Performance Computing Centre for Climate- and Earth System Research GCM model (http://www.dkrz.de/dkrz/intro_s). The land use types and distribution used for the analysis were those developed by EPA for the Phase 5 Chesapeake Bay Watershed Model (USEPA, in preparation). Gridded climate change data containing estimates of precipitation change (%) and air temperature change (degrees C) from the ECHM model were obtained from the Consortium for Atlantic Regional Assessment (CARA) web site (http://www.cara.psu.edu/climate/). These data grids were supplied on a seasonal (DecJanFeb, MarAprMay, JunJulAug, SepOctNov) basis. An overlay of subwatersheds from the Monocacy was used to select grid points associated with each subwatershed. For air temperature, the average of the selected grid points was added to the each value in the existing air temperature dataset. Potential evapotranspiration was then estimated based on the new air temperature values. For precipitation, only events in the top 10% (in terms of storm volume) were adjusted to reflect the increase. If precipitation had a seasonal decrease, events that contained the lowest 90% of the total volume were adjusted to reflect the decrease.

Modeling of the climate change scenario using HSPF resulted in a net increase of total nitrogen loads from the watershed of 10.7%. Detailed assessment was performed to better understand the source of the increased loads, as well as the opportunities for controlling these increases by changed management practices. Results are presented in Table 1. The last two columns of the table provide information on the percent change in unit loadings for each land use, and the percentage of the total watershed N loading increase from climate change attributable to each land use. Several results of this assessment are noteworthy:

- Changes in **unit** nutrient loadings for different land use types in the Monocacy watershed ranged from -4% to +37%.
- The impact of modeled climate change on land uses ranged from a reduction of total watershed N loads attributable to ‘hay without nutrients’ lands of 0.5% to an increase of total watershed N loads attributable to forest lands of 26%.

- Three land use/management types (nutrient management high till with manure, nutrient management low till, bare construction) comprising only 18% of the watershed result in 47% of the predicted increase in total watershed nitrogen loading.
- Differential vulnerability to climate change of different land uses and management practices was evident. For example, 'nutrient management high till with manure' lands contributed nearly as much increase to the watershed's total N loads as did forest lands (21.6% versus 26%, respectively), but the area dedicated to the former is only one fifth as large as the latter. The much greater unit loading rate computed for total N generated by the 'nutrient management high till with manure' lands as compared to forest lands (35.8 kg/ha versus 3.2 kg/ha, respectively) explains this result.

This type of analysis using CAT and the HSPF model can be used to identify regions and land uses potentially most sensitive to climate change and to guide the development of management responses. For example, the demonstration results in Table 1 suggest that management efforts to mitigate increased N loads attributable to the selected climate change scenario should be focused on high till agricultural land with manure application, low till nutrient management lands, and bare construction lands, since simulation results predicted that these three land uses accounted for over 45% of the increase in total N loads.

Sensitivity Assessment

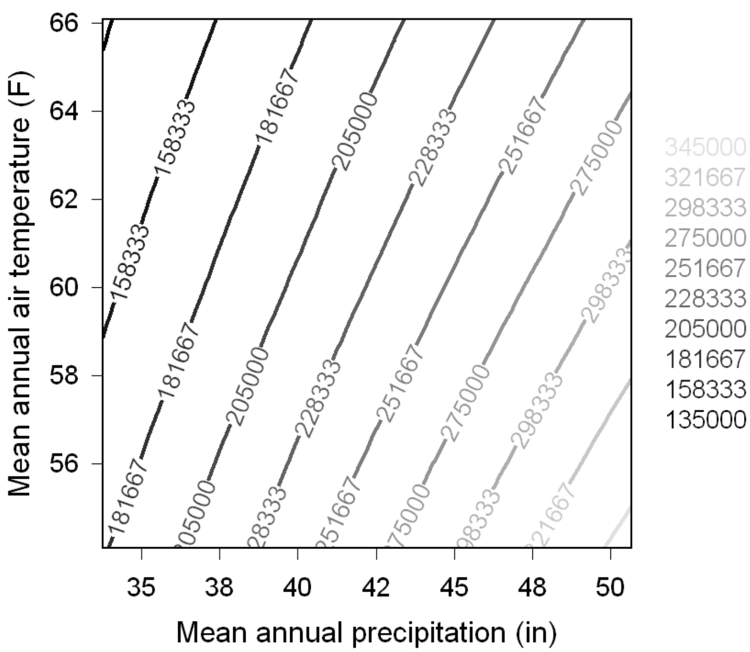

Figure 3. Annual Nitrogen Loading (pounds/yr) in the Western Branch of the Patuxent River, Maryland, as a Function of Mean Annual Precipitation and Mean Annual Temperature.

Figure 3 shows results from an example application of CAT to perform sensitivity analysis of pollutant loadings to changes in precipitation and air temperature. The fitted contours show the annual nitrogen loading (pounds/yr) in the Western Branch of the 230 km^2 Patuxent River, Maryland watershed as a function of annual precipitation and mean annual temperature. The plot is based on a series of 35 HSPF model simulations generated using the automated, iterative assessment capability of the BASINS CAT. Precipitation data were modified by increasing historical values by plus or minus 0, 5, 10, 15 and 20 percent. Temperature data were modified by adding 0, 2, 4, 6, 8, 10 and 12^{o}F to historical values. The contour plot illustrates that as precipitation increases across the watershed, nitrogen loads increase, reflecting increased runoff. As air temperature increases, nitrogen loads decrease in response to decreased runoff, a result of increased evapotranspiration. Quantitative understanding of the sensitivity of nitrogen loads to climate change scenarios such as the one developed in this example could help managers assess the risk of not meeting a management target that is presented by plausible climatic variability and change.

CONCLUSIONS

CAT was released to the public as a component of BASINS Version 4.0 in May, 2007. Consequently, its application history has just begun. The ability to assess climate change within the comprehensive watershed modeling framework that already existed in BASINS offers new, and we believe very promising opportunities for managers to understand and reduce risk by better incorporating information about climate variability and change into their decision making process.

ACKNOWLEDGMENTS

This work was funded by the U.S. Environmental Protection Agency under contracts # 68-C-01-037 and EP-C-06-029. The views expressed in this paper are those of the authors and do not necessarily reflect the views and policies of the U.S. Environmental Protection Agency.

Table 1. Change in total nitrogen load contribution attributable to selected climate change scenario in Monocacy River Basin, Maryland.

Land Use	Area (ha)	base conditions Load (kg/ha)	base conditions Total Load (kg)	climate change scenario Load (kg/ha)	climate change scenario Total Load (kg)	% Change in Unit Load	% of Total Change
forest	86581	2.34	202287	3.20	276935	36.9%	26.0%
nutrient management hitil with manure	17900	32.29	577995	35.76	640043	10.7%	21.6%
nutrient management lotil	24539	21.56	529020	23.36	573168	8.4%	15.4%
bare-construction	2535	40.62	102959	52.27	132488	28.7%	10.3%
lowtill with manure	5210	44.89	233892	48.93	254954	9.1%	7.3%
hightill with manure	3792	73.96	280488	78.81	298906	6.6%	6.4%
pasture	23079	5.37	123919	5.96	137598	11.0%	4.8%
nutrient management hay	16002	8.77	140300	9.56	153060	9.1%	4.4%
low intensity pervious urban	31408	5.71	179259	5.86	184027	2.7%	1.7%
harvested forest	875	49.54	43330	53.05	46399	7.1%	1.1%
high intensity pervious urban	8533	5.67	48401	5.80	49524	2.3%	0.4%
alfalfa	5505	12.21	67239	12.39	68199	1.4%	0.3%
nursery	1147	23.40	26845	24.08	27625	2.9%	0.3%
extractive	115	17.28	1988	22.03	2535	27.5%	0.2%
hightill without manure	183	50.91	9294	54.03	9863	6.1%	0.2%
hay with nutrients	4581	8.15	37324	8.23	37692	1.0%	0.1%
nutrient management hitil without manure	944	27.50	25966	27.68	26138	0.7%	0.1%
trampled	116	65.37	7582	65.38	7583	0.0%	0.0%
natural grass	3348	3.19	10680	3.07	10265	-3.9%	-0.1%
hay without nutrients	7245	6.24	45238	6.05	43838	-3.1%	-0.5%
total load			2694006		2980840	10.7%	

REFERENCES

Arnold, J.G. and N. Fohrer. 2005. SWAT2000: Current Capabilities and Research Opportunities in Applied Watershed Modeling. Hydrol. Process. 19(3): 563-572.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle Jr., T.H. Jobes, and A.S. Donigian, Jr. 2005. Hydrological Simulation Program - Fortran (HSPF). User's Manual for Release 12.2 U.S. EPA National Exposure Research Laboratory, Athens, GA, in cooperation with U.S. Geological Survey, WRD, Reston, VA.

Burns, I. S., S. Scott, L. Levick, M. Hernandez, D. C. Goodrich, D. J. Semmens, W. G. Kepner, and S. N. Miller. 2004. Automated Geospatial Watershed Assessment (AGWA) - A GIS-Based Hydrologic Modeling Tool: Documentation and User Manual Version 1.5. [PDF, 98 pp., 1.78 MB] EPA/600/C-06/001 and ARS/137460.

Clough, J. S., and R. A. Park. 2006. AQUATOX (Release 3) Modeling Environmental Fate and Ecological Effects in Aquatic Ecosystems, Addendum to Release 2 & 2.1 Technical Documentation. U.S. Environmental Protection Agency, Washington, DC.

Fitzpatrick, J.J., J.C. Imhoff, E.H. Burgess and R.W. Brashear. 2001. Assessment and Use of Hydrodynamic, Land-based Runoff, and Fate and Transport Models. Project 99-WSM-5 Final Report. Published by the Water Environment Federation, Alexandria, VA.

IPPC (Intergovernmental Panel on Climate Change), 2001. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press. Cambridge, United Kingdom.

Johnson, T. and J.L. Kittle, Jr. 2006. Sensitivity Analysis as a Guide for Assessing and Managing the Impacts of Climate Change on Water Resources. AWRA Water Resources Impact. Vol 8:5, pp.15-18.

Pielke, R.A. Sr. and L. Bravo de Guenni (Eds.). 2004. How to Evaluate Vulnerability in Changing Environmental Conditions: Part E. *In*: Vegetation, Water, Humans and the Climate: A New Perspective on an Interactive System. Global Change – The IGBP Series. P. Kabat et al. (Eds.). Springer, pp. 483-544.

Saerwitz, D., R.A. Pielke, Jr. and R.Byerly, Jr. 2000. Introduction: Death, Taxes, and Environmental Policy. *In*: Predictions: Science, Decision Making and the Future of Nature. D. Sarewitz, R.A. Pielke, Jr. and R. Byerly, Jr. (Eds.). Island Press, Washington, DC, pp. 1-7.

USEPA (U.S. Environmental Protection Agency). 2007. BASINS 4.0. U.S. Environmental Protection Agency, EPA-823-C-07-001, Washington, DC.

USEPA (U.S. Environmental Protection Agency). In Preparation. Chesapeake Bay Phase 5 Community Watershed Model. EPA XXX-X-XX-008, Chesapeake Bay Program Office, Annapolis MD. January 2008.