Impact of Best Management Practices on Water Quality

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***Abstract*— As the world experiences rapid growth and urban development, the management of our water resources is of increasing importance. Policy-makers and regulators are faced with the prospect of making decisions today to assure adequate supply of clean water for tomorrow's world. Water supply, however, is a local problem. And, issues of adequate water supply are the result of intertwined human and natural forces. Humans require, consume, and waste precious water. Nature of its own, and owing to increased pressures of climate change, adds an element of unpredictability. Here we describe two approaches to better understanding the "water problem." One is an existing participatory simulation enabling human players to engage dynamically in decision-making about water. The other is a large-scale, high fidelity simulation-only model that provides greater depth of understanding into this complex human and natural system. This was computed via IBM's World Community Grid (wcgrid.org).**

I. Introduction

Access to adequate quantities of clean water is an increasingly important issue faced by policymakers at all levels. With reduced budgets and competing demands for public services, hard policy choices aimed at solving the "water problem" are easily set aside. And, being widely perceived as a "free" commodity, the public generally does not appreciate the magnitude of the problem.

The dimensions of the problem, both the quantity and quality of water, are temporal, spatial, and behavioral. Implementing new water initiatives involves long-term planning and infrastructure projects. The historical pattern of development, driven largely by population growth, often does not consider the availability of an adequate and sustainable water supply. And, increasing demand for water creates a classic Tragedy of the Commons situation (Ostrom, 2009). Add to this, the looming problem of climate change, the problem becomes more uncertain.

This report describes how this problem is being examined in the Chesapeake Bay Watershed in the United States. The Chesapeake Bay Watershed is the largest estuary in U.S. covering large parts of six Mid-Atlantic States and the District of Columbia, an area of some 64,000 square miles with a population of 17.2M persons in 2010 (see Figure 1). This watershed does not suffer from a lack of water, but rather from the deleterious effects of human activity on the Bay's environment. Previous attempts have been made to organize collective action to mitigate these impacts without success (*Chesapeake 2000*, 2000). In May 2009, the Obama Administration issued Executive Order 13508 mandating the restoration and sustainability of this precious national resource (Executive Order 13508, 2010).

To gain deeper insight into this coupled natural and human system, a large-scale simulation model of the Chesapeake Bay was developed. It models the state of the Bay's health over two, twenty-year periods from 1990 to 2010 and from 2010 to 2030 at a monthly scale. Spatially, the model has fidelity to the level of one acre and incorporates river flow using over 1,000 river segments. The population of the watershed is captured at the level of the individual household.

The model was executed on IBM's World Community Grid (World Community Grid, 2011). This provides the opportunity to explore a large number of scenarios to better understand the potential impacts of policy choices as the individual states implement their respective plans to achieve Bay health goals as postulated by the Presidential Executive Order.

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II. THE UVA BAY GAME®

A multidisciplinary team of researchers at the University of Virginia took first steps at modeling the Chesapeake Bay Watershed with human participation through the development of a participatory simulation–the UVa Bay Game® (Learmonth et al., 2011).

This participatory simulation, developed and launched in April 2009, consists of a high-level simulation model of the Chesapeake Bay developed as a systems dynamics model with a game interface allowing human players to interact with the simulation model as it moves through ten, two-year rounds simulating twenty years—2000 - 2020. The first five rounds (ten years) of the participatory simulation cover historical years where key data are known; the last five two-year rounds use stochastically projected values for key model variables.

Participants take on an assortment of roles including crop farmers, livestock farmers, land developers, watermen, and their corresponding regulators. Players are distributed into seven sub-watersheds. At each round of game play, participants review information about their decisions and individual performance in previous rounds; they also see regional (sub-watershed) results and limited global (watershed-wide) results. Based on their analysis and interpretation of this information, they then have the opportunity to revise their decisions for the next round. The UVa Bay Game can accommodate as many as 166 live players but typical gameplays have from 16 to 40 live players.

The UVa Bay Game is regularly played in university classes at UVa and a number of other universities through the world. Additionally, regulators and policy-makers from the National Oceanographic and Atmospheric Administration (NOAA); the U.S. Environmental Protection Agency (EPA); and the U.S. House of Representatives among others have played the UVa Bay Game. More interestingly, game plays with industry executives have proven quite successful as they seek to better understand the economic risk associated with their exposure to issues of water supply.

The underlying simulation model in the UVa Bay Game is at a very high level of aggregation—spatial representation is at the level of seven major sub-watersheds; temporal representation is at two-year intervals (although the underlying model uses a quarter-year step); and with human agents (players) each representing on the order of hundreds or thousands of actual persons. The results produced by the model are, however, accurate—in the parlance of simulation modeling, the results have been verified against empirically reported data through 2010.

The goal of the UVa Bay Game model is not to attain deep fidelity to the natural processes happening in the Chesapeake Bay, but rather for game players, in their various roles, to gain understanding of the complexity of this human and natural system and to realize that their human decisions and actions can lead to positive outcomes; but ultimately, uncontrollable Nature rules.

III. COMPUTING FOR SUSTAINABLE WATER

With the high-level of aggregation in the UVa Bay Game model, there is limited ability to examine the impact of proposed policy choices such as the effectiveness of agricultural and urban Best Management Practices (BMPs); land use changes over time; and population growth. Consequently, a more detailed model with greater fidelity to spatial and temporal dimensions is required.

A model with finer spatial detail, a monthly versus quarterly time step, and the ability to represent the impact of human activities was developed. At this level of fidelity, it would not only consist of a simulation program and database of extraordinary size, but with varying only a few parameters, each over a limited range of choices, would require a (combinatorially) large number of experiments. This computational challenge led to the search for computational resources on which to run very large number of high fidelity simulation-model-only experiments.

The World Community Grid, supported by IBM, is such a computational resource (www.worldcommunitygrid.org). World Community Grid consists of over 2 million computers donating their unused computer cycles to problems of social importance. The volunteered computers have screen savers installed which, when started during idle time, run computationally intensive programs in the background. When the owner of the computer resumes his or her work and thus interrupts the screen saver, the background research program stops and waits until the next idle time when it then resumes.

In 2010, World Community Grid chose two water-related projects to place on the grid for execution (IBM, 2010). One of these is Computing for Sustainable Water—a name chosen to differentiate the high fidelity, simulation-only model of the Chesapeake Bay Watershed from the participatory simulation version. This simulation-only model was launched on the World Community Grid in April 2012.

A. The CFSW Model

Like the participatory simulation version, this model is focused on the health (quality) of the Chesapeake Bay as measured by the total nitrogen and phosphorus loads (nutrients) entering the Bay. The model calculates the amount of nitrogen and phosphorus applied to areas of the watershed and follows how those nutrients are either taken up in the soil or run off, eventually reaching the Bay. The water quality problem in the Chesapeake Bay Watershed, and similar regions, is caused by excess nutrients flowing into the watershed.

Nutrients, such as nitrogen and phosphorus, are extremely beneficial to the soil in enhancing crop growth and keeping lawns green and healthy. Too much of a good thing, however, is problematic. Excess nutrients flowing into the Bay lead to excessive algal growth. Algae both cloud the water preventing sunlight from reaching underwater grasses and, when they die, sink to the bottom consuming necessary oxygen. The lack of oxygen creates hypoxic and anoxic regions in the Bay (dead zones) that are inhospitable to aquatic species. In the case of the Chesapeake Bay, this is most challenging to the blue crab population, an industry important to the economic heath and sustainability of the Bay.

While there are naturally occurring sources of nutrients in the environment and these do reach the Bay, the excess nutrient problem is a direct result of human action—agricultural fertilization, lack of proper waste removal on animal farms, land development, storm water runoff, increased area of impervious surfaces, septic system use, and atmospheric deposition (a large proportion of the nitrogen in the Bay is the result of air pollution). Such sources of excess nutrients are called non-point sources. They are not easily monitored or controlled. In contrast, point sources such as wastewater treatment facilities and industrial sites are quite effectively monitored and controlled through existing policy actions, such as the Clean Water Act and Clean Air Act.

In this model, all human action is simulated. But, through the ability to create and simulate a wide range of scenarios, the impacts of human action and a range of possible policy actions to mitigate the effects of those actions, can be efficiently and effectively examined.

B. Spatial dimension of the model

Much of the data used to construct the model comes from diverse sources including the Chesapeake Bay Program Office's Phase 5 Watershed Model, the Bureau of Labor and Statistics, the US Census Bureau, and the National Agricultural Statistics Service.

The Chesapeake Bay Watershed includes all, or a portion of, 197 distinct Federal Information Processing (FIPS) coded areas. These roughly correspond to counties and cities. Some are further subdivided based on variations in altitude (which affects rainfall measurements) giving a total 238 "parcels." Each parcel consists of portions of 25 identified land uses (Table 1).

Lastly, using a cutoff flow rate of at least 100 gallons per minute, 952 river segments are identified. Combining parcels, land uses, and river segments, the spatial dimension of the model consists of approximately 35,000 "areas" consisting of a variable number of farms (about 33,000 in all) and a fixed number (2,259) of non-farm areas. The "area" then is the smallest spatial unit in the model. Farm acreage comprises about 10.2M acres of the approximately 41.2M acres in the Chesapeake Bay Watershed. Simulated farm sizes are distributed according to USDA estimates.

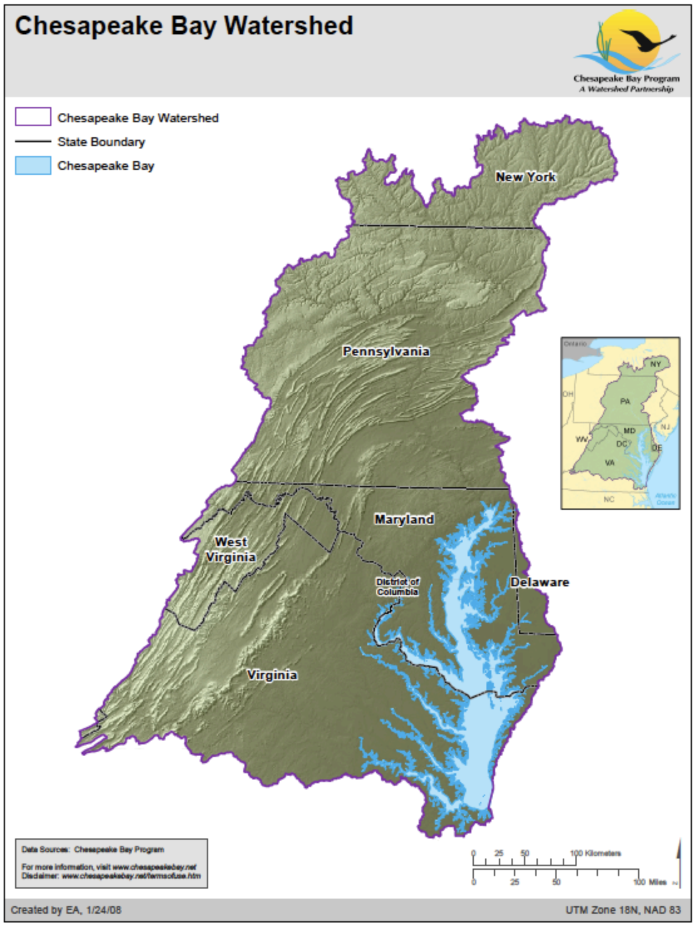

Fig. 1: The Chesapeake Bay Watershed (Source: Chesapeake Bay Program Office)

Animal Feeding Operations	Nutrient Management - Alfalfa
Alfalfa	Nutrient Management - High Tillage w/ Manure
Bare-Construction	Nutrient Management - High Tillage w/o Manure
Extractive (Active/Abandoned Mines)	Nutrient Management - Hay
Forests, Woodlots and Wooded	Nutrient Management - Low Tillage
High Tillage without Manure	Nutrient Management - Pasture
Harvested Forest	Pasture
High Tillage with Manure	High Intensity Developed, Pervious
Hay without Nutrients	Low Intensity Developed, Pervious
Hay with Nutrients	Degraded Riparian Pasture
High Intensity Developed Impervious	Nursery
Low Intensity Developed Impervious	Open Water
Low Tillage with Manure	

Table 1. Land uses

Fig. 2 Land Area Representation

C. Population

The model distributes the population of the watershed over the approximately 35,000 areas in units of households. The number of persons per household is a parameter of the model with a typical mean value of 2.4 and a standard deviation of 0.5 persons. Thus, the model has approximately 7 million households. All impacts of human action and decision-making are captured at the level of the household, for example, whether it uses a sewer connection versus a septic system.

The population of the Chesapeake Bay Watershed over the twenty-year simulated period grows in accordance with U.S. Census Bureau projections at the level of each parcel. The population increase in a parcel is then apportioned based on population density within each area in the parcel.

IV. Model Agents

The Computing for Sustainable Water simulation model is an agent-based model. That is, there are autonomous microscale elements (agents) within the model that take independent action. The overall observed behavior of the simulation model (at the macroscale) is then a result of the non-linear interaction of the microscale agents. Without a central coordinating authority dictating local agent decisions, macroscale outcomes are largely unpredictable (in the long run). Thus, simulation modeling is the approach of choice to understand the behavior of complex human and natural systems. In the Computing for Sustainable Water model, both natural and human elements are modeled with this property of agency.

A. Areas

An area is the most common type of agent in the model. Each area consists of an amount of acreage, a land use, a population situated in some number of households, and a set of nutrient contribution functions. An area may have a different nutrient contribution function for each month of the year. For example, a farmer may choose not to fertilize cropland in wintertime. An area also has an edge-of-field (EOF) ratio to simulate the transfer of nutrients from an area to its neighboring river segments. Each area can have its own EOF multiplier function for each nutrient. These functions calculate EOF ratios from the flow of the river segment.

Within each time step, every area is queried for its nutrient contribution and that contribution's source. Internally, the area agent calculates this number by delegating the question to its households and adding the results of its own nutrient contribution function, if any. An area's nutrient contribution source is determined by its land usage. The model supports multiple sources for an area agent's nutrient contribution.

Every area has the possibility of employing zero or more BMPs that modify its total nutrient contribution. Further, an area may employ a BMP over only a subset of its total acreage. For example, an urban area may have separate storm water sewage systems covering 25% of its acreage. Farms may use continuous no-till practices on a portion of their fields. In determining total nutrient contribution, the area calculates the effect of every BMP in use by first calculating the efficiency of the BMP in that area, the acreage covered by the BMP, and which nutrients are affected by it, and scales the total contribution accordingly.

$$Nutrientload = EOF \times Landsegmentpercentage \times (Contribution\ BMP \times efficiency \times coverage)$$

B. Households

A household is a simple agent that contains a number of persons and some acreage of lawn. At least prior to the increase of agricultural land devoted to corn production (ethanol), lawns covered more acres in the United States than corn (Milesi, 2005). Studies have estimated that lawn fertilization can have a significant nutrient export to the watershed. During summer months, each household can decide to fertilize its lawn, or not. The model assigns randomized fertilization frequencies from zero to four times per year. Once determined, a household will always fertilize with the same frequency every year.

The human inhabitants of a household create an amount of human waste every month. This sewage—biological, from household cleaners, or other sources—is handled via either a septic tank or a sewer system, depending on the land usage where the household is located. Each area can have a different ratio of septic/sewer systems, and can specify different per-person nutrient loads. Septic contributions are not subject to EOF scaling.

C. River Segments

A river segment is the smallest unit of waterway in the model. Each river segment feeds exactly one downstream river segment. The amount of water that flows from one river segment to the next is represented in the model by a flow variable, which is scripted for every month and year during a simulation experiment. The river segments contain a set of flow multiplier functions that simulate how a given flow affects "in-stream" processes such as deposition, scour, or de-nitrification. The flow multiplier function can be different for each nutrient in each river segment.

The flow multiplier is effectively a discount factor for nutrients, a situation that occurs in the real world. For example, Virginia regulations state that nutrients added to the Chesapeake Bay Watershed can be traded among regulated entities. However, the trade is weighted based on utility locations in the watershed (VPDES, 2012).

V. Modeling Nutrient Flow

The process begins with nutrient introduction to each area based on land use. Total nitrogen (TN) is composed of NH3N (ammonia), NO3N (nitrate), and ORG-N (organic nitrogen) and total phosphorus (TP) is composed of PO4-P (phosphate) and ORG-P (organic phosphorus). Then nutrient uptake is calculated based on land use and month of the year (capturing seasonality).

Once nutrients have been introduced and some percentage has been taken up, the rest are presumed to leave the area in the form of nutrient runoff. Depending on the land use type, a percentage of the excess nutrients are transferred to the river segments adjacent to the area. River segments then transfer their nutrients to the next downstream river segment. This river-segment-to-river-segment transfer is limited by a user-configurable discount factor, which simulates the deposition of nutrients into the streambed.

A. Best Management Practices

Policy-makers and regulators have used Best Management Practices in agriculture and in urban environments to incentivize practices that are considered beneficial to the health of the Chesapeake Bay. While these BMPs appeal to common sense as beneficial actions, there is scant empirical evidence of their effectiveness. The simulation model is designed to allow BMPs individually and in combination to be tested to ascertain the corresponding nutrient loads reaching the Bay. The 23 BMPS included in the CFSW are given below in Table 2.

BMP	BMP Name
1	Agricultural Waste Management System-Livestock
2	Agricultural Waste Management System-Poultry
3	Barnyard Runoff Control
4	Conservation Tillage
5	Continuous No-Till
6	Cover Crops (Spring and Winter Planting)
7	Dry Detention Ponds
8	Erosion & Sediment Control
9	Dry Extended Detention Ponds
10	Filtering Practices
11	Riparian Grass Buffers-Non-Point Source
12	Riparian Grass Buffers-Point Source
13	Riparian Forest Buffers-Point Source
14	Riparian Forest Buffers-Non-Point Source
15	Infiltration Practices
16	Loafing Lot Management
17	Mortality Composters
18	Off-Stream Watering without fencing
19	Precision Grazing
20	Upland Precision Grazing
21	Urban Nutrient Management
22	Wetland Restoration
23	Wet Ponds & Wetlands

Table 2. Best Management Practices

VI. Computing for Sustainable Water Experimental Results

The computer code implementing this model is written in C++ and uses a relational database during execution. The actual code size is approximately 9,200 lines and requires about 300MB of memory. A single run (experiment) of the model with a given set of parameters used between 1.5 and 3.5 hours of CPU core time. In all, 19,131,876 experiments were executed.

A. Baseline Experiments

Nutrient flow into the Chesapeake Bay is largely determined by surface water flow coming from rainfall and snowmelt. Of course, annual flow is a natural process that cannot be predicted accurately. In these simulation experiments, natural processes are not modeled, either historically or in the forecast periods. Rather, an assumption of a "normal" flow volume is assumed from which to measure the effect of BMPs individually and in combination.

For the simulated period from 1990 through 2010, the U.S. Geological Survey provides historical data on nutrient flow both modeled and observed. Tables 3 and 4 below summarize these values from 1990 to 2009. The load data are for non-point sources only. The CFSW code only accounts for these non-point loads.

Year	**Flow (10^9 gal./day)**	**Total N (USGS Model)**	**Total N (USGS Observed)**
1990	48.86	253,179,362	230,615,931
1991	54.29	291,397,500	281,214,524
1992	39.04	203,279,113	165,763,858
1993	65.28	344,042,146	350,499,731
1994	69.16	352,798,486	361,744,960
1995	38.72	200,574,659	163,128,664
1996	74.33	379,364,328	396,015,461
1997	58.04	288,206,634	280,265,093
1998	68.51	334,817,023	339,164,593
1999	29.47	155,007,743	105,864,346
2000	45.63	208,553,588	175,116,321
2001	34.00	166,918,739	122,707,466
2002	29.34	152,878,514	105,648,883

2003	76.92	354,574,776	366,645,849
2004	76.27	428,688,685	466,871,630
2005	56.62	296,769,255	296,865,165
2006	50.09	255,394,093	241,588,761
2007	51.39	244,748,812	228,220,857
2008	48.02	226,814,654	207,831,362
2009	40.98	183,216,714	152,113,886

Table 3. USGS Reported Flow and Non-Point N Loads

Year	Flow (10^9 gal./day)	Total P (USGS Model)	Total P (USGS Observed)
1990	48.86	15,801,947	9,209,640
1991	54.29	15,863,841	13,013,731
1992	39.04	15,985,377	4,943,915
1993	65.28	16,012,260	21,236,927
1994	69.16	16,043,929	20,730,316
1995	38.72	16,083,925	6,422,934
1996	74.33	16,111,742	32,284,096
1997	58.04	15,890,831	14,429,501
1998	68.51	15,899,179	22,962,871
1999	29.47	15,860,295	1,877,883
2000	45.63	15,799,651	5,493,209
2001	34.00	15,902,306	3,041,099
2002	29.34	15,755,468	1,763,020
2003	76.92	15,726,736	30,847,586
2004	76.27	15,730,598	43,041,612
2005	56.62	15,683,268	18,244,292
2006	50.09	15,655,871	14,056,605
2007	51.39	15,641,132	12,684,238
2008	48.02	16,890,704	10,044,080
2009	40.98	15,261,665	5,359,499

Table 4. USGS Reported Flow and Non-Point P Loads
Source: http://www.chesapeakebay.net/indicators/indicator/nitrogen_loads_and_river_flow_to_the_bay1

Flow volume is reported annually in billions of gallons per day and is estimated from flow gauges above and below the geological fall line. The reported years are for "water years" which begin in October. The annual nitrogen (N) and phosphorous (P) loads are given in pounds. It is clear from the observed measurements that natural processes are at work in the observed variation. For example, in September 2003, Hurricane Isabel struck much of the Chesapeake Bay Watershed leading to extraordinary flow volume crossing the water year boundary. Likewise, the corresponding observed N and P loads were extremely high. The USGS model data (N only) also reflect these extreme events because the model was adjusted in 2013 to account for these events. Summarizing these data, the 20-year averages and first and third quartile values are given below:

	Flow Volume	USGS Modeled N Load	USGS Observed N Load
1st Quartile	40.98	202,603,000	165,105,059
Mean	**52.70**	**266,061,241**	**251,894,367**
3rd Quartile	65.28	337,123,304	341,998,377

	Flow Volume	USGS Modeled P Load	USGS Observed P Load
1st Quartile	40.98	15,729,632	5,459,782
Mean	**52.70**	**15,880,036**	**14,584,353**
3rd Quartile	65.28	15,992,098	20,856,969

Table 5: Summary Statistics of USGS Model and Observed N and P Loads

These values do not account for BMPs that may have been used in the Chesapeake Bay Watershed; hence they do not provide a basis for assessing CFSW experimental runs. The N and P loads include only non-point sources; point sources and atmospheric deposition are excluded.

The CFSW experimental runs assume "average" annual flow volume (~53B/gal per day) and no extraordinary climatic events that would mask the effects of the BMPs. To begin the analysis of the initial CFSW experimental runs, a series of baseline experiments were conducted. The first experimental runs were conducted for the years 1990 through 2009 with no BPMs operational. These were followed by experiments with each BMP turned on individually to isolate its potential impact in reducing N and P loads, that is, testing each BMP's individual effectiveness. For the single base experiment of no-BMPs (bmp-0), the summary statistics taken over the 20 simulated years from1990 to 2009 are shown below.

	bmp-0 N Load	bmp-0 P Load
1st Quartile	261,672,654	15,721,088
Mean	**261,868,252**	**15,880,036**
3rd Quartile	262,206,277	16,011,139

Table 6: Summary Statistics for the Base Case of no BMPs Operative

The results above cannot be directly compared with USGS model results because they are from different simulation models using different assumptions. However, it is useful to comment on the differences. With the N loads, the CFSW model shows a larger mean load over the 20-year interval, albeit with a smaller variance. One explanation is that the CFSW results (bmp-0) have no BMPs operative whereas the USGS model has some combination of BMPs operative in its model. As for the P loads, the mean value is slightly higher for bmp-0 and there is again a smaller variance. The mean values are identical due to centering of the distributions here.

To assess the individual BMPs (bmp-1 through bmp-23), the null hypothesis is that there is no statistically significant effect from the application of a given BMP (bmp-x); that is, there is no difference between the mean of the 20-year simulated load (N or P) with a BMP operative ("turned on") and the base case of no BMPs (bmp-0). The alternative hypothesis is that the mean of the case with an individual BMP operative is less than the mean of the no-BMP experiment. When the null hypothesis is rejected in favor of the alternative, this is statistical evidence of the efficacy of the BMP. One-sided Student's t-tests were used to test each individual BMP against the base case.

	N Load			**P Load**		
BMP	**t-statistic**	**p-value**		**t-statistic**	**p-value**	
1	-0.5794	0.2833		-2.8177	0.0040	***
2	1.9025	0.9669		-0.7996	0.2145	
3	2.0569	0.9766		-1.2769	0.1049	
4	-37.5482	0.0000	***	-22.0426	0.0000	***
5	0.8586	0.8020		-1.2361	0.1122	
6	-1.8144	0.0388	**	-2.3989	0.0107	**
7	-4.3216	0.0001	***	-11.5046	0.0000	***
8	1.4547	0.9225		0.1187	0.5469	
9	0.3914	0.6510		-4.9344	0.0000	***
10	2.7439	0.9952		-0.8145	0.2112	
11	1.0179	0.8423		-2.4417	0.0101	**
12	0.4469	0.6709		-1.3994	0.0850	*
13	0.4825	0.6836		-2.0812	0.0221	**
14	0.7442	0.7691		-2.184	0.0176	**
15	1.2479	0.8901		-0.7347	0.2342	
16	0.3712	0.6435		-2.1189	0.0207	**
17	-0.4297	0.3351		-1.5286	0.0678	*
18	1.8966	0.9672		-2.236	0.0160	**
19	1.0179	0.8423		-2.4417	0.0101	**
20	0.0697	0.5276		-1.0844	0.1425	
21	2.2832	0.9859		-0.9234	0.1813	
22	2.9808	0.9973		-1.3361	0.0955	*

23	-2.2594	0.0148	***	-4.9788	0.0000	***

Table 7: Student's t-tests of Individual BMPs versus Base Case of No BMPs
* = significant at $\alpha = 0.10$; ** = significant at $\alpha = 0.05$; *** = significant at $\alpha = 0.01$

Examining the results above, it is somewhat surprising that only four of the 23 BMP in wide use show significant effect on the nitrogen (N) load delivered to the Chesapeake Bay. BMP 4 is highly significant and this is not unexpected. This BMP is associated with the practice of Conservation Tillage. This particular method of land preparation leaves a significant amount of crop residue on the soil surface after harvesting which prevents soil erosion and the consequent runoff of nutrients into water sources.

BMP 6, Cover Crops, has a similar effect in that farms plant grasses after harvest with the resulting benefit of reducing runoff as well as providing non-chemical nutrients to the soil when these grasses are plowed under during Spring planting thus providing a natural source of nutrients.

The significance of BMP 7 is surprising. This BMP is associated with the provisioning of Dry Retention Ponds. A Dry Retention Pond is an area designed to hold water runoff water, especially after a storm and heavy snowfall. Such ponds, while reducing the effect of storm water runoff, are not generally associated with reducing nutrient loadings (N or P). Lastly, BMP 23–Wet Ponds or Wetlands, provide a natural buffer to collect nutrient runoff from farms and fields. Its significance is not surprising.

The phosphorous (P) loadings show a much wider effectiveness of individual BMPs. BMPs 1, 4, 7, 9, 11, and 23 are highly significant (1% level of significance). BMPs 6, 13, 14, 18, and 19 are significant at the 5% level while BMPs 12 and 22 are significant at the 10% level.

It is noteworthy that in both the N and P loadings, BMPs 4, 6, and 7 demonstrate significant effectiveness. While BMPs 4 and 6 are similar in the nature of their impact, the effectiveness of BMP 7 remains surprising.

B. Further Experimentation

The Computing for Sustainable Water project, in theory, could test all possible combinations of the 23 BMPs plus combination of the other ten parameters listed under "Other Model Parameters" above. This would have created an enormous search space–about 8.5 billion experiments. Rather, the CFSW team chose a smaller group of experiments involving 21 of the BMPs individually and four combined sets of BMPs, in two groupings. These are:

Group 1 (7 individual BMPs; 3 combinations):

- One run with all BMPs and combinations set to "normal" effectiveness (1.0)
- Seven individual BMPs: 4, 5, 6, 8, 11, 12, and 13
  - One run each with the individual BMPs set to 0.9 effectiveness
  - One run each with the individual BMPs set to 1.1 effectiveness
- Three Combinations {1, 2, 3, 17}, {7, 9, 22, 23}, and {10, 15}
  - One run each with the combination set to 0.9 effectiveness
  - One run each with the combination set to 1.1 effectiveness

Group 2 (14 individual BMPs):

- One run with all BMPs in the group set to "normal" effectiveness (1.0)
- Fourteen individual BMPs : 1-3, 10, 14-23
  - One run each with the individual BMPs set to 0.9 effectiveness
  - One run each with the individual BMPs set to 1.1 effectiveness

Both Groups were examined historically over the twenty-year period 1990-2009 and then forecast for the twenty-year period 2010-2029. Again, these forecast experiments did not account for climatic events, i.e., none were explicitly forecast.

As with the base case analysis above, Student's t-tests were used on mean annual loads taken over the 20-year test period. The following the null and alternate hypotheses were tested:

H0: Mean(BMP[0.9]) > Mean(BMP[1.0])
Ha: Mean(BMP[0.9]) ≤ Mean(BMP[1.0])

H0: Mean(BMP[1.1]) < Mean(BMP[1.0])
Ha: Mean(BMP[1.1]) ≥ Mean(BMP[1.0])

H0: Mean(BMP[1.1]) < Mean(BMP[0.9])
Ha: Mean(BMP[1.1]) ≥ Mean(BMP[0.9])

Table 8 contains the t-test results of the analysis of Group 1, Nitrogen and Phosphorus loads for the period 1990-2009. As can be seen, there is only one statistically significant difference noted (**in bold**), that of BMP 13 on the nitrogen loading. This result may be spurious because the test of the mean loading at the 1.1 level versus the 0.9 level should also prove significant for consistency. The conclusion here is that among these experimental tests, as grouped, there is little discernible difference in 20-year average loadings as a result of the corresponding BMPs' effectiveness.

Similar tests were run on Group 2 1990-2009 and both groups for the period 2010-2029, these are not shown here because there were no statistically significant changes in N and P loads as a result of the various BMPs and BMP combinations tested in these experiments. In addition to the Student's t-tests shown here, additional statistical test were performed with the same result. Two-sample Wilcoxon tests (also known as the Mann-Whitney U-test) were performed on the mean values with no significant results. And, to test a distributional assumption on the 20-year sets, the Kolmogorov-Smirnov two-sample test was performed on all pairs. These non-parametric tests show no statistically significant difference on the empirical distributions derived from the CFSW experimental runs.

VII. CONCLUSION

From the initial analyses presented here, two principal conclusions emerge. From the initial baseline testing of each BMP individually against the case of no BMPs at all, results indicating the efficacy of many of the BMPs are encouraging. These results will inform policy-makers as to where to encourage sustainable practices to reduce nitrogen and phosphorous loads reaching the Chesapeake Bay. Arguably, these results can be extended to other regions of the United States with suitable customization.

Less encouraging are the results of the various combinations of BMPs, both historically and as forecast into the future. An argument can be made that these outcomes are the result of confounding; that is, mixing the impacts of multiple effects in ways that individual impacts are masked by interactions.

Group 1 Nitrogen loads 1990-2009						
BMP	**0.9 v. All 1.0**		**1.1 v. All 1.0**		**0.9 v. 1.1 level**	
	t	p	t	p	t	p
4	1.194	0.120	0.966	0.830	-0.256	0.400
5	1.151	0.129	0.527	0.699	-0.640	0.263
6	0.563	0.288	0.221	0.587	-0.355	0.362
8	0.701	0.244	0.772	0.778	0.150	0.559
11	0.711	0.241	0.476	0.682	-0.173	0.432
12	1.004	0.161	0.162	0.564	-0.735	0.235
13	***2.032***	***0.025***	0.994	0.837	-0.874	0.194
1, 2, 3, 17	0.797	0.215	0.977	0.833	0.146	0.558
7, 9, 22, 23	0.499	0.311	0.377	0.646	-0.098	0.461
10, 15	0.884	0.191	0.281	0.610	-0.570	0.286

Group 1 Phosphorous loads 1990-2009						
BMP	**0.9 v. All 1.0**		**1.1 v. All 1.0**		**0.9 v. 1.1 level**	
	t	p	t	p	t	p
4	0.275	0.392	0.342	0.633	0.071	0.528
5	0.158	0.438	0.094	0.537	-0.065	0.474
6	-0.011	0.505	0.108	0.543	0.121	0.548
8	0.159	0.437	0.160	0.563	-0.003	0.499
11	0.051	0.480	0.045	0.518	-0.008	0.497
12	0.174	0.432	0.123	0.549	-0.050	0.480
13	0.105	0.459	0.152	0.560	0.053	0.520
1, 2, 3, 17	0.138	0.446	0.018	0.507	-0.119	0.453
7,9, 22, 23	0.005	0.498	0.237	0.593	0.234	0.592
10, 15	0.244	0.404	0.108	0.543	-0.136	0.446

Table 8: Student's t-tests of Group 1 Experiments–1990-2009

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