# Integrated Watershed Economic Model for Non-Point Source Pollution Management in the Upper Big Walnut Creek Watershed, OH

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## 1. Introduction

Today, non-point source pollution (NPS) is one of the major sources of water quality impairments globally (UNEP, 2007). In the US, nutrient pollution is the leading cause of water quality issues in lakes, streams, and estuaries (USEPA, 2002). Nutrient enrichment in an ecosystem would seriously degrade the integrity of that ecosystem and impair the variety of services provided by the ecosystem (Carpenter et al., 1998). In recognition of the value of ecosystem services, the United States Environmental Protection Agency (USEPA) mandates individual states to implement the Total Maximum Daily Load to limit the off-land loading of nutrients (USEPA, 2002). Additionally, federal and state governments are working on expanding the use of conservation management practices in agricultural lands to reduce the pollution load from agriculture (Ice, 2004; Mausbach and Dedrick, 2004).

The cost of expansion of conservation management in agriculture has to come from the society. In addition, farmers have to bear the opportunity cost of allocation of land for conservation management. Thus, economic efficiency criteria need to be applied to prioritize conservation choices. In this context, economic efficiency would imply the combination of crop mix and conservation practices that would equalize the marginal social costs and benefits of conservation management expansion. Hence, information about economic efficiency of conservation practices are important in NPS policy making, so that planners, conservation experts and local watershed groups can prioritize conservation program in their watershed and show the worthiness of expansion of conservation management. However, the ever-increasing water quality impairment by agricultural NPS in US clearly shows that the task of designing an economically efficient policy framework for controlling the NPS is challenging, which can be categorized into two:

1. NPS is generated and transported over a highly heterogeneous biophysical realm with tremendous spatial and temporal variability and uncertainty. Thus, quantifying location specific NPS load across a landscape is not an easy task.
2. Practices applied for crop production, i.e. input to and output from farms varies across the landscape, which have a critical role in magnitude of NPS generation (Naevdal, 2001; Carpenter et al., 1999; Ribaudo et al. 1999). In addition, economic cost of crop production and conservation practices also varies across space.

Thus, derivation of detailed response functions of nutrient loading and crop output with different level of adoption of conservation practices across a heterogeneous landscape would be a daunting task, especially when the NPS generation and transportation processes are compounded by both human and biophysical factors (SAB, 2008; Elofsson, 2003). In order to evolve a policy analysis framework for addressing the issues identified above, redefining the NPS issues in a multidisciplinary background with clear understanding of both biophysical processes and socio-economic context of the watershed is necessary. Thus, an integrated watershed economic modeling (IWEM) would be useful to partition the biophysical and anthropogenic effects of the NPS generation and transport in a watershed and to draw the blueprints of conservation management guidelines. Such an IWEM would have three components, a biophysical process component, an economic behavior component and a tool to integrate both the biophysical and economic components. The biophysical component uses climatic, soil and terrain properties on spatial scale along with site specific management variables to simulate a broad range of land-uses and conservation practices, interactions among conservation practices and variations in crop yield with different conservation options. Thus, the biophysical process component of the IWEM could preserve the heterogeneity of the watershed, and able to simulate the behavior consistent with established scientific understanding (Antle and Capalbo, 2001). The economic behavior component would be able to capture the economic rationale of selection of technology and crop-mix options along with explicit description of social costs and benefits associated with reduction in nutrient loading with different conservation technologies. A dynamic optimization framework that explicitly portrays conservation management options and resulted reduction in nutrient load, with an objective function of maximizing net social benefit of adoption of conservation practices, can be a tool to integrate biophysical and economic components of IWEM. Thus, in this study we use an IWEM approach for a comprehensive assessment of the costs and benefits, including co-benefits, of various conservation management options to derive economically efficient conservation options for the watershed, which is generally lacking in NPS management research (SAB, 2008). The IWEM is developed and implemented in four steps.

1. A watershed simulation model, Soil Water Analysis Tool (SWAT) was used to simulate crop yield, nutrient load (Nitrogen only, here after N) with different levels of adoption of conservation technologies.

2. The SWAT results of different heterogenic land-units were used to derive an aggregate watershed scale continuous crop production function and N loading function (watershed scale N balance) with adoption of conservation practices.
3. The societal value of water quality improvement is estimated by using non-market valuation methods and these estimates are used to calibrate a social damage cost function of N loading.
4. The social damage cost of N loading is internalized in objective function of dynamic programming. The soil N balance equations of different technology crop combinations represent the state transition functions of Dynamic Programming.

The IWEM is applied to the Upper Big Walnut Creek (UBWC) watershed of Ohio, which was identified by Ohio EPA as an impaired watershed due to nutrient enrichment from current agricultural management practices (Ohio EPA, 2005). The UBWC encompasses perennial and intermittent streams that drain into Hoover Reservoir, which serves as a primary source of drinking water supply and a favorite local recreational site for residents of Columbus and surrounding communities (Ohio EPA, 2005).

Section 2 briefly describes the methodological approach used in the paper, specifically for the derivation of costs and benefits of water quality improvement, generation of the possible best management practices (BMP) for the watershed using the already developed watershed model and finally the integration of the two sub-models, which is followed by results and discussion, and the final section describes some concluding thoughts.

## Methods

### 2.1 Simulation of conservation management scenarios in SWAT

SWAT is a physically based, watershed-scale continuous time simulation model operating on a daily time step (Arnold et al., 1998). SWAT can be used to simulate long-term impacts of land cover and land use practices and management strategies on water flow, crop/vegetative growth and water quality parameters such as sediment and nutrient load from watershed (Saleh et al., 2000; Vache´ et al., 2002; Chu et al., 2004; Hu et al., 2007). SWAT divides a sub-watershed into smaller discrete hydrological response units (HRU) with homogeneous biophysical properties using slope, soil and land cover maps. In UBWC, a total of 376 HRUs were generated by SWAT. After calibration and validation of the SWAT model for UBWC, the conservation management options were simulated for deriving crop and conservation technology specific production functions and N loading function (A comprehensive description of SWAT modeling was reported Surendran Nair, 2010). The simulations of best management practices (BMP) were completed in several steps.

***Step-1 Crops and cropping rotation for simulations***

As corn, soybean and wheat are the predominant crops cultivated in the UBWC, these crops were considered in different rotations for reducing the nutrient load from the farm. The specific rotations selected were: corn-corn (C-C), corn-soybean (C-S) and corn-soybean-wheat (C-S-W).

***Step-2 Fertilizer application strategies***

The three crop rotations were separately analyzed for split application of N fertilizer, ${}^{2}/_{3}{}^{rd}$ of total N fertilizer applied at planting and ${}^{1}/_{3}{}^{rd}$ one month after planting as side dressed (Witter, 2006).

***Step-3 Tillage strategy***

Conservation tillage was selected as a promising conservation method for the UBWC. Thus selected crop rotations were separately analyzed for the impact of conservation tillage adoption for reduction in nutrient loading.

***Step-4 Cover crop strategy***

It is reported that cover cropping with existing cropping system would reduce the quantity of nutrient transport from the farm (Staver and Brinsfield, 1998). As rye (*Secale cereale* L.) has been used successfully as a cover crop, it was introduced in each of the selected cropping rotations for the simulation exercise.

***Step-5 Vegetative buffer***

A 10 m vegetative buffer is also included in the BMP list as a nutrient load reduction strategy (Lovell and Sullivan, 2006; Witter 2006) and watershed area lost from agricultural production was derived.

Simulations of each of the crop rotation-technology combinations were performed separately. The existence of crop rotation-technology combination in baseline was accounted for while deriving watershed scale crop production and N loading functions. Each scenario was simulated for 25 years from 2010 using climatic inputs for UBWC created by weather generator in the SWAT. The average annual outputs for the watershed were derived.

## 2.2 Baseline crop production function (BPF)

The baseline N production function for corn and wheat, and phosphorus (P) production function for soybean were estimated by using SWAT model for the UBWC watershed. The SWAT derived crop yields for the watershed were generated by running the SWAT with varied levels of N application for corn and wheat, and P for soybean. A quadratic relationship between applied nutrients and yield were established by regressing applied nutrients against simulated yields of for different crops for the watershed.

$$BPF_i = a_i + b_i \times x_i - c_i \times x_i^2 \qquad (1)$$

$i$= crop and $x$ = nutrients applied for crop production, N fertilizer for corn and wheat, and P for soybean. Now the per hectare profit ($\pi_{ih}$) can be written as,

$$\pi_i \quad = [(a_i + b_i \times x_i - c_i \times x_i^2) \times P_i]\text{-}\ P_x \times\ x_i\text{-}V_i(Y_i) \qquad (2)$$

$P_{yi}$ , $P_x$ and $V_i(Y_i)$ are unit price of crop output, nutrient input and cost of other variable inputs, respectively.

## 2.3 Baseline soil nitrogen stock

The baseline soil N balance ($N_t$) equation was derived for the watershed by the SWAT model. The soil-N balance equation consists of N applied for crop production ($n_t$), N carried over from last year ($N_{t-1}$), fraction of N uptake by crop ($\alpha$) and the fraction of the soil-N flushed-out from the watershed ($\gamma$), which can be written as,

$$N_t = (N_{t-1} + n_t) - \gamma(N_{t-1} + n_t) - \lambda(N_{t-1} + n_t) \qquad (3)$$

So the baseline N load can be represented as,

$$\text{N Load}_t = \lambda(N_{t-1} + n_t) \quad (4)$$

However, in the case of soil-N balance for soybean, N fixation component (N-Fix) also has to be included. N-Fix is introduced in soil-N balance equation as,

$$\text{NFix} = \varphi * \text{Y} \quad (5)$$

$\varphi$ is watershed specific N fixation factor, which is derived by dividing average N fixed by soybean with average soybean yield (Y) from SWAT model results. Thus, Soil-N balance for soybean is,

$$N_t = (N_{t-1} + n_t + \text{NFix}_\text{t}) - \lambda(N_{t-1} + \text{NFix}_\text{t}) \quad (6)$$

$$\text{N Load}_i = \lambda(N_{it-1} + \text{NFix}_\text{t}) \quad (7)$$

Generally, BMP technologies are applied simultaneously by a farmer. Thus three different technology sets were generated for scenario analysis in DP with current crops cultivated in the UBWC watershed (45% corn, 45% soybean and 10% wheat).

- Technology Set-1: The current level of agricultural production
- Technology set-2: Cover crop, vegetative buffer and conservation tillage
- Technology set-3: Technology set-2 and split-N fertilizer application

**2.4 Change in baseline production and soil-N balance with level of technology adoption**

The watershed scale production and soil-N balance for each crop-rotation and technology combinations were calculated. It was expressed as an exponential function of baseline yield and % area of technology adoption.

$$PF_{hij} = BPF_{hij} e^{\beta h_{ij} * Ah_{ij}} \quad (8)$$

Where $h$, $i$, $j$ and $k$ represents crop rotation, crop in each of the crop rotation and technology set, respectively. $Ah_{ij}$ represents percent adoption of technology. To translate the problem into a simple DP framework, the present study assumed full adoption of technology ($Ah_{ij} = 100$). Thus, $\beta_{hij}$ was multiplied by $100$ in the production function. However, changes in crop production due to simultaneous adoption of BMP's technologies (Technology set-2 and Technology Set-3), average yield deviation from the baseline for Technology set-2 and Technology Set-3 were used. Thus,

$$APF_{hij} = \left[\left(BPF_i \times average\left(e^{\beta_{hij} \times 100}\right)\right)\right] \quad (9)$$

In a similar way, the N loading rate with different conservation technologies was also adjusted.

$$N\_\text{load}_{h,ij} = N\_Load_{hij} e^{\theta_{hij} * 100} \quad (10)$$

Where $\beta$ and $\theta$ are parameters that represent changes in crop yield and N load from baseline due to full adoption of technology. As separate simulations were made for each crop-rotation technology combination, to reduce number of simulation it is assumed that simultaneous application of the conservation technologies would result in a multiplier impact on pollution load reduction and other nutrient processes in the soil. Thus, for a given crop rotation (h=1), the nutrient loading from different BMP technologies can be expressed,

$$N\_\text{load}_{1ij} = N\_Load_{1ij} \prod_j e^{\theta_{1ij} \times 100} \quad (11)$$

and

$$AN\_\text{load}_{ij} = \left[\left(N_{\text{load}\ i} \prod_j e^{\theta_{ij} \times (1-A_{buffer}) \times 100}\right) \times e_b{}^{\acute{\theta}_{ij} * 100}\right] \quad (12)$$

In the case of buffer, 100 % of adoption means that all the HRU's in UBWC watershed adopted with 10 meter buffer filters and $e_b{}^{\acute{\theta}_{ij} * 100}$ is the pollution reduction by using buffer.

## 2.5 Change in cost with level of technology adoption

The cost function consists of variable cost of applied N and variable cost of other inputs expressed as function of yield, social cost of pollution load and technology cost of conservation practices. The applied N would not change across the conservation technologies except for N reduction options. Additional cost involved in adoption of conservation technologies would be applicable to split-N application, cover cropping and maintenance of buffer strip. In the case of split-N application, the additional application cost is calculated as $25 per hectare (Hoorman, 2009). However, in the case of cover cropping, cost of seed, sowing and killing of the crop have to be accounted, that is estimated as $110 per hectare (Hoorman, 2009). The vegetative buffer cost was calculated based on Sohngen 2003.

## 2.6 The social damage cost of nitrogen loading

The quantification of costs of conservation management program is reasonably straight forward. However, the benefits estimations of water quality improvements or benefit lost due to water quality impairments are relatively difficult (Baylis et al., 2004). This is because most of the benefits come in the form of non-marketed goods and services. In general, any enhancement in quality of water resources provides two broad classes of economic benefits: withdrawal benefits and in-stream benefits (Feenberg and Mills, 1980). Withdrawal benefits include direct consumption of water (e.g. household use) and the water that is used as an input in other production processes (e.g. industry and agriculture). In-stream benefits include use-value of water quality (e.g. swimming, boating, sport- fishing and others) and non-use value of water quality (e.g. improvement in land and aquatic biodiversity). Thus, water quality impairment would result an opportunity cost on society, economic value of opportunities that a society lost due to the decline in water quality. This can be termed as a social damage cost (SDC) of water pollution. Therefore, we can establish a direct relationship between the amount of pollution and SDC through a social damage function.

Since a functional form of the social damage function is not readily available, a possible option is to make an approximation based on theory. As damage cost by N loading logically increase with N stock in the water body, SDC and marginal SDC could be assumed as a continuous function of pollution stock. In addition, another important piece of information needed to make an approximation for a SDC function is to obtain information about the shapes of the function. Therefore it is important to find out what could be the probable shape of social damage function with pollution levels. As a starting point, we set a zero level of N loading. It is clear that at a zero level of N loading, SDC will be zero. The next logical step is to determine the upper boundary of N loading with SDC still zero.

It was stated earlier that an ecosystem has an innate capacity to assimilate some portion of N load, resulting a reduction in pollution load to the downstream water reservoir at two levels, one is in the channel connecting ($\delta$) the farm and the water reservoir ($\varphi$). Thus, zero SDC can be extended up, until the assimilation potential of an ecosystem is not reached ($\delta + \varphi$). Once the N loading surpasses the natural assimilation of an ecosystem, the SDC curve will go up with the N load from the farm. Beyond this point, with more N export to streams and reservoir, the proportion of N in the water will increase. In this situation, two things have to be considered.

- A higher level of pollution will also increase the probability of exposure for the different players in an ecosystem to the polluted environment. For example, as N loading goes up, there is a greater probability that the higher number of dependent population would be exposed to poor quality water
- At higher concentration levels of N, the magnitude of the damage caused by the pollutant will also increase.

Thus, SDC will increase more-than-proportionately with an incremental N load to water reservoir. This indicates that a social damage function is likely to have a convex shape in this range (Fig. 1). The convexity of the damage cost function ensures that the marginal costs are increasing with increase in the N load. The increasing concern about the water quality impairment in UBWC watershed shows that the assimilation potential has reached its limit and the N export is now in the range of convex shaped function. So we can define SDC as,

$$D = f(N_{wt}) \tag{13}$$

which is assumed to be convex, smooth and increasing with the level of the N load.

$$D = f(0) = 0, \ \frac{\partial D(\bullet)}{\partial N_{wt}} > 0, \quad \frac{\partial^2 D(\bullet)}{\partial N_{wt}{}^2} > 0 \tag{14}$$

So, the equation (14), total SDC function and marginal SDC can be rewritten in the following form to fix the parameter.

$$\text{Total SDC(TDC)} = \alpha(N_{wt})^{\eta} \tag{15}$$

$$\text{Marginal SDC(MDC)} = \eta \times \alpha(N_{wt})^{\eta-1} \tag{16}$$

where $\alpha$ is a coefficient and the exponent $\eta$ is the elasticity of damage cost function.

In UBWC, two recent estimates of non-market value of water quality benefit are available,

1. In UBWC, a detailed study on withdrawal benefits (drinking water quality) and non-use value (land and aquatic biodiversity) of water quality improvements by using conjoint analysis have already been documented (Tennity, 2006).
2. In-stream benefit estimates of water quality improvement in UBWC, specifically boating and fishing have been reported by using combined revealed and stated preference approach (Surendran Nair, 2010).

As per Tennity (2006) study, If N loading from agricultural farm in UBWC is reduced to 50%, which would results in 40% reduction N level in the stream and in the reservoir and .In addition, Tennity also reported that this level of N load reduction would bring social benefit of $321.1 per hectare in the streams and $242.06 per hectare in the reservoir. The recreational value of water quality improvement showed that, if water quality in the watershed is improved to EPA standards, recreational benefit to streams and the reservoir was calculated as $3.35 and $63.75, respectively. It is assumed that a reduction of N loading by half from farm to stream would help to achieve the EPA water quality standards for the UBWC watershed. Therefore, both the above-mentioned estimates were added to derive full social benefits of water quality improvement, which is $324.45 for streams and $305.81 for downstream reservoir. These estimates was used to derive marginal SDC, which is $'s/1 unit change in Kg N load. As said earlier, Tennity's estimates show that a 50% reduction N inputs leads to a 40% reduction in N in the stream. Thus 40% reduction N load from current level (SWAT result from Technology Set-1) of 14.5 Kg/ hectare to stream N is worth $321.10 per hectare, or 321.10/ (.4*14.5), or $55.90 per ha per Kg of N and $ 58.6 per ha per kg for the reservoir (initial N load to reservoir is 13.05 Kg per hectare from SWAT result with Technology Set-1).

To fix the value for $\eta$, a series SDC were generated for current level of loading with different $\alpha$ and $\eta$ values was compared with the above calculated values for stream and reservoir, and found that the quadratic SDC estimates were close to the calculated SDC value. So, the elasticity parameter was fixed as 2 (Table.1).

Now we can calibrate $\alpha$ as $\alpha$ = Marginal SDC/ (2*N), thus, $\alpha$ = 55.9/(2*14.5) = 1.93 for streams and $\alpha$ = 58.6/(2*13.05) = 2.24. Thus, $1.93(N_{stream})^2$ and $2.24(N_{reservoir})^2$ are total SDC for the stream and the reservoir respectively. At current N load (14.5 kg per hectare in the stream and 13.05 Kg per hectare to the reservoir), total damages in the stream and the reservoir are $405.56 and $382.26 respectively for stream and reservoir. However, these values are the present values. We assume a 30 year program to annualize the estimates at 5 % interest rate and calculated the annual total damages and annual marginal damages, and then re-calibrate the damage function to get the annual damage function, which is $0.125(N_{stream})^2$ and $0.146(N_{reservoir})^2$. This puts total damages at around $51 per ha per year for the stream and the reservoir at current level of N loading, which is about 5% of the net per hectare cash returns to agriculture.

Three different dynamic programs were specified for three different crop rotation scenarios. In the case of corn-soybean rotation and corn-soybean-wheat rotations, total profit is weighted with the proportion of area under each crop. Each of the dynamic programs was sequentially run for different technology scenarios.

### 2.7 Dynamic program specification

Three different DP problems were specified for C-C, C-S and C-S-W crop rotations. The Planner's problem is deterministic, with finite horizon.

- State variable:
  - Soil-N level $N_t$
  - Nitrate level in the downstream water reservoir $N_{wt}$
- State space:

- $N_t \in [0, \infty)$
- $N_{wt} \in [0, \infty)$

- Action variable:
  - One action variable (N application for corn) for C-C rotation DP
  - Two action variable for C-S rotation DP
    - N fertilizer application for corn and P fertilizer application for soybean
  - Three action variable for C-S-W rotation, N fertilizer application for corn.
    - N fertilizer application for corn and wheat and P fertilizer application for soybean.
- Action space: $n_t \in (0, \propto]$ for both N and P fertilizers

- State Transition function:

$$AN\_\mathrm{load}_{ij} = \left[\left(N_{\mathrm{load}\ i} \prod_j e^{\theta_{ij} \times 100}\right) \times e_b{}^{\hat{\theta}_{ij} \times 100}\right]$$

The Bellman equation can be expressed as,

$$\max_{,N_{ij}} = \left[\left(\frac{1}{1+r}\right)^t \sum_{1}^{t} \sum_{i=1}^{I} \sum_{j=1}^{J} \left[p_j \ APF_{ij} - p_N N_{ij} - p_o \left(APF_{ij}\right) - TechCost_{ij}\right] \times [1 - Area_B] - \alpha_{wt} \left(\varphi\left(AN\_\mathrm{load}_{ij}\left(N_{ijt-1} + n_{ijt}\right)\right)\right)^{\eta}\right] + V\theta\left(\delta\varphi\left(AN\_\mathrm{load}_{ij}\left(N_{ijt-1} + n_{ijt}\right)\right)\right)$$

Where $Area_B$and $\varphi$ are fraction of area under buffer and coefficient of assimilation within the stream and in the reservoir.

Coefficients of baseline production and N loading functions for C-C, C-S and C-S-W are given in Table 4.1 and coefficients of technology and crop rotation specific crop yield and N loading functions are described in the result section.

| | |
|---|---|
| **Production function** | |
| Corn | $1.615+0.082n-0.0002n^2$ |
| Soybean | $1.88+0.0254\,p-0.0002p^2$ |
| Wheat | $1.752+0.055\,n-0.0003n^2$ |
| **N Balance Function** | |
| N Uptake coefficient for C-C | 0.73 |
| N Load coefficient C-C | 0.081 |
| Soybean N_fixing coefficient | Min (80,43.53*Yield) |
| N Uptake coefficient for C-S | 0.77 |
| N Load coefficient C-S | 0.072 |
| Wheat uptake coefficient | 0.81 |
| Wheat N Load coefficient | 0.061 |
| **Cost and Prices** | |
| Price of Corn ($/ton) | 159.74 |
| Price of Soybean($/ton) | 330.60 |
| Price of Wheat($/ton) | 146.97 |
| Price of Nitrogen Fertilizer($/kg) | 1.57 |
| Price of Phosphorus fertilizer($/kg) | 1.70 |
| Technology Cost for split N application ($/ha) | 25.00 |
| Technology Cost for cover crop ($/ha) | 110.00 |

| **BMP** | **Corn-Corn** | **Corn-Soybean** | | **Corn-Soybean-Wheat** | | |
|---|---|---|---|---|---|---|
| **Technology** | **Corn** | **Corn** | **Soybean** | **Corn** | **Soybean** | **Wheat** |
| **Change in Crop Production** ($\boldsymbol{\beta} \times \mathbf{100}$) | | | | | | |
| Cons. Tillage | -0.01 | -0.01 | -0.02 | -0.01 | -0.03 | -0.01 |
| Cover Crops | -0.01 | -0.01 | -0.03 | -0.01 | -0.03 | -0.03 |
| N-Split | -0.02 | -0.02 | 0.00 | -0.03 | 0.00 | -0.01 |
| Buffer | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **N Loading by crop** ($\boldsymbol{\theta} \times \mathbf{100}$) | | | | | | |
| Cons. Tillage | -0.06 | -0.06 | -0.07 | -0.07 | -0.07 | -0.02 |
| Cover Crops | -0.07 | -0.07 | -0.05 | -0.06 | -0.06 | -0.07 |
| N-Split | -0.06 | -0.07 | -0.00 | -0.08 | -0.00 | -0.07 |
| Buffer | -0.32 | -0.32 | -0.32 | -0.32 | -0.32 | -0.32 |

**Table 4.2 Parameter values for corn-corn, corn-soybean and corn-soybean-wheat production functions**

**Table 2 Coefficients of baseline production function and nutrient balance used in the model**

### 2.8 Solving Bellman equation thorough collocation

We attempted to solve the problem as detailed through the collocation method, a approach for the numerical solution partial differential equations, implemented using MATLAB 7.1. In collocation technique, the basis function and number of collocation nodes in basis function has to be specified. In this exercise, we have used splin basis function and 100 collocation nodes to derive the approximation of Bellman equation. By using basis function and collocation nodes we can express the value function approximant (Miranda and Fackler, 2002). The state variables spaces ( $N_t$ and $N_{wt}$ ) were specified first, followed by the action variable. In collocation method, a state space is bounded within a specific bound on a real line. In this study, the lower bound of state space was fixed as '0' and the upper bound as 100. Then, action variable was defined as continuous, but within simple bounds, $a(s) \le x \le b(s)$. In this paper, '0' and infinity are fixed as lower and upper bounds, respectively. An approximate solution to the Bellman equation using collocation method is arrived by using the CompEcon Toolbox routines (Miranda and Fackler, 2002).

## 3 Results

The base run was performed with two different cases with the objective of maximizing farmer's private profit (total receipt- total variable cost).

Case-1: C-C, C-S and C-S-W crop rotations were analyzed separately. Crop rotation is represented in the DP by assigning a fraction of area as a weighing factor for each of the crop in a crop rotation. Thus, to specify C-S rotation, corn and soybean was weighted by 0.5.

| | **Private (Revenue-Input cost)** | **Ohio** |
|---|---|---|
| **Corn** | | |
| Yield (t/ha) | 9.84 | 10.27 |
| Fertilizer-N (Kg/ha) | 174.5 | 174.26 |
| Profit ($/ha) | 558.00 | 476.00 |
| **Soybean** | | |
| Yield (t/ha) | 2.68 | 3.63 |
| Fertilizer-P (Kg/ha) | 42 | 48 |
| Profit ($/ha) | 470 | 462 |
| **Wheat** | | |
| Yield (t/ha) | 4.15 | 5.01 |
| Fertilizer-N (Kg/ha) | 80.03 | 92.15 |
| Profit ($/ha) | 140.16 | 179.04 |

**Table 3. Comparison of baseline result with field crop enterprise budget-2009**

However, in C-S-W rotation corn, soybean and wheat were weighted by 0.45, 0.45 and 0.1 respectively. Case-1 was attempted to compare DP derived outputs for each of the C-C, C-S and CSW rotations with the current level of agricultural production in the state of Ohio. The result was compared with the field crop enterprise budget for 2009 for crop yield, N application and profit, which showed that base run results were close to the average farm practices in Ohio (Table 3). In general, yields derived from DP for corn, soybean and wheat were lower than that from farm budget data for the state of Ohio. In the case of N application, the average N rate for corn obtained from DP modeling was close to that reported in farm budget for Ohio. But, the profit value, especially for corn, in DP was higher than the average profit for an Ohio farm.

Case2:

However, 90% of the cultivated area in the UBWC watershed is occupied by corn and soybean (45% each for corn and soybean). Thus, in case2 run was accomplished with C-S-W rotation with a weighing factor of 0.45 for corn and soybean and 0.1 for wheat.

| | | **Private (Revenue-Input cost)** | **Profit with internalized pollution cost** |
|---|---|---|---|
| **Corn-Soybean-Wheat** | | | |
| Yield (t/ha) | C | 9.64 | 6.15 |
| | S | 2.81 | 2.20 |
| | W | 4.03 | 2.50 |
| N load(kg/ha) | | 12.87 | 6.63 |
| Fertilizer (Kg/ha) | | 170.51 | 103.41 |
| DP value function ($/ha) | | 7950 | 5163 |
| Reservoir-N (kg) | | 11.77 | 6.03 |

**Table 4. Profit maximization with and without cost of pollution**

The yield of corn, soybean and wheat were close to the average reported yield of the state of Ohio and discounted profit (value function) was $7950 for C-S-W (Table 4).

In the next step, the cost of pollution was accounted while calculating the profit from crop production. This could be a socially ideal case, where cost negative externality of a production process is internalized to minimize the value lost to the society due to pollution. This can be viewed as a non-point pollution taxing from government (Tax-based approach). Thus, under this case, a farmer needs to make a payment for each unit of N load that comes from his farm. The result showed that crop yield of each of the crops was reduced when cost of the pollution was internalized in profit. Moreover, nutrient load from the farm under each of the crop rotations was also reduced drastically to $ 5163 due to the reduction in fertilizer application (Table 5).

In the next step, model was run with Technology set-2 (C-S-W with conservation tillage, cover cropping and vegetative buffer) and Technology set-3 (N-split application with conservation tillage, cover cropping and vegetative buffer).

In the case of C-S-W rotation, N load to the reservoir was the lowest with technology set-3, which is higher than socially desirable pollution load (Maximizing profit with internalizing pollution cost). Additionally, value function and crop yields were higher than crop production with internalized cost of production scenario. However, both the technology sets crop production level and value function were less than as compared to private profit maximizing scenario. Thus, it is clear that with current crop rotation with multiple conservation technologies farmers cannot reach their private level of profit and crop production.

| | **Private (Revenue-Input cost)** | **Profit with internalized pollution cost** | **Technology Set-2** | **Technology Set-3** |
|---|---|---|---|---|
| Yield (t/ha) C<br>S<br>W | 9.64<br>2.81<br>4.03 | 6.15<br>2.20<br>2.50 | 8.72<br>2.41<br>3.07 | 9.04<br>2.35<br>3.80 |
| N load(kg/ha) | 12.87 | 6.63 | 7.25 | 7.03 |
| Fertilizer (Kg/ha) | 170.51 | 103.41 | 112.46 | 137.48 |
| Discounted profit ($/ha) | 7950 | 5163 | 5430 | 5940 |
| Reservoir-N (kg) | 11.77 | 6.03 | 6.53 | 6.33 |

**Table 5. Results after application of conservation technologies with current cultivation**

Additionally, two more scenario analysis were also attempted to understand N loading under two probable crop rotation scenarios in the future,

1. Complete area under watershed follow a C-C rotation and
2. Complete area under watershed follow a C-S with each of the technology sets.

In the case of C-C rotation scenario, the N loading to the reservoir was lowest under technology set-3. Additionally, both technologies showed higher value function than that under profit maximization which accounted for cost of pollution. The N loading under the two technology sets was close to that of profit maximization which accounted cost of pollution (Table 6).

| | **Private (Revenue-Input cost)** | **Profit with internalized pollution cost** | **Technology Set-2** | **Technology Set-3** |
|---|---|---|---|---|
| Yield(t/ha) | 9.64 | 6.15 | 8.75 | 9.12 |
| N load(kg/ha) | 12.87 | 6.63 | 125.00 | 149.00 |
| Fertilizer (Kg/ha) | 170.51 | 103.41 | 9.50.00 | 11.02 |
| Discounted profit ($/ha) | 7950 | 5163 | 8037.00 | 8982.00 |
| Reservoir-N (kg) | 11.77 | 6.03 | 9.19 | 8.55 |

**Table 6. Results after application of conservation technologies with C-C rotation**

As far as the C-S rotation is concerned, both technology sets showed the same pattern as in C-C rotation. The yield of corn in C-S was higher than that in C-C with lower level of N application, which might be due to the availability of biologically fixed N from soybean. The value function of the C-S was lower than that of C-C rotation under both the technology cases. However, pollution load to the reservoir from both the technology sets in C-S were lesser than that of C-C rotation (Table 7).

| | **Private (Revenue-Input cost)** | **Profit with internalized pollution cost** | **Technology Set-2** | **Technology Set-3** |
|---|---|---|---|---|
| Yield(t/ha) | 9.64 | 6.15 | 8.75 | 9.12 |
| N load(kg/ha) | 12.87 | 6.63 | 6.83 | 7.52 |
| Fertilizer (Kg/ha) | 170.51 | 103.41 | 132.04 | 137.16 |
| Discounted profit ($/ha) | 7950 | 5163 | 6075.00 | 6132.81 |
| Reservoir-N (kg) | 11.77 | 6.03 | 6.15 | 6.77 |

**Table 7. Results after application of conservation technologies with C-S rotation**

## 4 Conclusions

A dynamic programming-based economic optimization approach was used in this study to integrate the watershed model with an economic model. The watershed modeling results from essay 1 and the benefit estimates from essay 2 were used to specify the objective and transition functions of the dynamic program. Model is developed for the entire watershed by considering it as a single homogeneous one hectare unit. The watershed model was used to simulate the baseline and conservation technology-specific production function and nutrient loading functions. Two sets of conservation technologies were developed for the watershed. One with cover cropping, conservation tillage and vegetative buffer stripes and the other with split nitrogen fertilizer application, cover cropping, conservation tillage and vegetative buffer stripes. The baseline crop production results were close to the Ohio field crop enterprise budget. In addition, N loading in baseline simulations was also in line with the modeled results of adjacent watershed. The analysis revealed that under no restriction on pollution loading, farmers would apply a maximum of 170.51kg/ha of N and the value function would be $7950 under C-S-W rotation. However, after introducing the social cost of pollution in objective function, the fertilizer application rate was reduced to 103 kg/ha. The analysis of conservation management options revealed that each of the crop rotation and technology combination would give higher value than the present level of production with internalized pollution cost. Within the crop-technology combinations, split-N application, conservation tillage, cover crop showed the lowest pollution load to the reservoir along with higher value function. Thus, it could be concluded that the present level of private profit and yield levels are not realized by adopting both the technology sets considered in this study. Additionally, more area under C-C and C-S rotation would result in more pollution load to the reservoir.

## 5 References

Alexander, R.B., R.A. Smith, and G.E Schwarz. 2000. "Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico". *Nature* 403: 758-761.

Ateh, C.M., and J.D. Doll. 1996. "Spring-planted winter rye (*Secale cereale*) as a living mulch to control weeds in soybean (*Glycine max*)". *Weed Technol*. 10: 347–353.

Carpenter, S.R., D. Ludwig, and W.A. Brock. 1999. "Management of eutrophication for lakes subject to potentially irreversible change". *Ecological Application.* 9 (3): 751-771.

Carpenter, S. R., N. F. Caraco, D. L.Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998 . "Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Application.* 8( 3): 559-568.

Dinnes, D.L., D.L. Karlen, D.B. Jaynes, T.C. Kaspar, J.L. Hatfield, T.S. Colvin, and C.A. Cambardella. 2002. "Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils". *Agronomy Journal* 94:153-171.

Elofsson, K. 2003. "Cost-effective reductions of stochastic agricultural loads to the Baltic Sea". *Ecological Economics*. 47: 13– 31.

Hall, R.O, and J.L. Tank**.** 2003. "Ecosystem metabolism controls nitrogen uptake in streams in Grand Teton National Park, Wyoming". *Limnology Oceanography*. 48: 1120-1128.

Heimlich, R.E., K.D. Wiebe, R. Claassen, D. Gadsby, and R.M. House. 1998. "Wetlands and agriculture: Private interests and public benefits". Agricultural Economics Report 765. U.S. Department of Agriculture, Economic Research Service, Washington, DC, 94 pp.

Hoorman, J., 2009. Personal communication.

Kaspar, T.C., J.K. Radke, and J.M. Laflen. 2001. "Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion". *Journal of Soil Water Conservation*. 56:160–164.

Mausbach, M.J., and A.R., Dedrick. 2004. "The length we go—measuring environmental benefits of conservation practices". *Journal of Soil Water Conservation*. 59 (5): 96A-103A.

Miranda, M.J., Fackler, P.L., 2002. "Applied computational economics and finance". Cambridge, Mass.: MIT Press.

Mitsch, W.J., J.W. Jr. Day, J.W.Gilliam, P.M. Groffman, D.L. Hey, G. Randall and N.Wang. 1999. "Reducing nutrient loads, especially nitrate-nitrogen to surface water, groundwater, and the Gulf of Mexico". Topic 5 *Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, pp. 111.

Naevdal, E., 2001. "Optimal regulation of eutrophying lakes, fjords, and rivers in the presence of threshold effects". *American Journal of Agricultural Economics*. 83(4): 972-984.

Nakoa, M., and B. Sohngen. 2000. The effect of site quality on the costs of reducing soil erosion with riparian buffers. *Journal of Soil Water Conservation*. 55(2): 231-237.

Ohio EPA., 2005. “Total maximum daily loads for the Big Walnut Creek Watershed”. http://www.epa.state.oh.us/dsw/tmdl/BigWalnutCreekTMDL.html.

Peterson, B.J., W.M. Wollheim, P.J. Mulholland, J.R.Webster, and J.L Meyer. 2001. “Control of nitrogen export from watersheds by headwater streams”. *Science* 292 (5514): 86 – 90.

Randall, G.W., J.A. Vetsch, and J.R., Huffman. 2003. “Nitrate losses in subsurface drainage from a corn–soybean rotation as affected by time of nitrogen application and use of nitrapyrin”. *Journal of Environmental Quality*. 32: 1764–1772.

Reddy, K.N., 2001. “Effects of cereal and legume cover crop residues on weeds, yield, and net return in soybean (*Glycine max*)”. *Weed Technology*. 15: 660–668.

Reddy, K.N., and R.M. Zablotowicz. 2003. “Glyphosate-resistant soybean response to various salts of glyphosate and glyphosate accumulation in soybean nodules”. *Weed Science.* 51: 496-502.

Ribaudo, M.O., R.Horan, and M,E.Smith.1999. “Economics of water quality protection from nonpoint sources: theory and practice”. Agricultural Economics Report 728. U.S. Department of Agriculture, Economic Research Service, Washington, DC.

SAB., 2008. “Hypoxia in the Northern Gulf of Mexico: An update” EPA science advisory board. pp. 333.

Seitzinger, S.P., T.N. Wiegner, and R.Styles. 2002. “Bioavailability of DON from natural and anthropogenic sources to estuarine plankton”. *Limnology and Oceanography*. 47: 353–366.

Staver, K.W., Brinsfield, R.B., 1998. “Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain”. *Journal of Soil Water Conservation*. 53:230–240.

Sundermeier, A., 2009. “Crop rotation and tillage effect on crop yield”. http://agcrops.osu.edu/research/documents/rotationtillagefinal.pdf

Tennity, C., 2005. “A Conjoint analysis study of perceived demand in Central Ohio for specific agricultural natural resource conservation practices”. MS. Thesis submitted to the Ohio State University.

UNEP., 2007. “Global environmental outlook 4: Environment for development”. Progress Press Ltd Valletta, Malta pp. 572.

USEPA., 2002. “National water quality inventory 2000 report”. EPA-841-R-02-001. Washington, DC.

USGS., 1999. “The quality of our nation’s waters: nutrients and pesticides”. Circular 1225, Reston, Virginia, 82 pp.

Vitosh, M.L., and J. W. Johnson, and D.B. Mengel. 1995. “Tri-state fertilizer recommendations for corn, soybeans, wheat and alfalfa”. *Extension Bulletin E-2567*.

Wagger, M.G., and D.B. Mengel. 1993. “The role of non-leguminous cover crops in the efficient use of water and nitrogen”. 115–127. In: Hargrove, W.L., (ed.) Cropping strategies for efficient use of water and nitrogen. *ASA Special Publication* 51, Madison, WI.

| $\alpha$ | $\eta$=1 | | $\eta$=2 | | $\eta$=3 | | $\eta$=3 | |
|---|---|---|---|---|---|---|---|---|
| | Stream | Reservoir | Stream | Reservoir | Stream | Reservoir | Stream | Reservoir |
| 0.1 | 0.58 | 0.52 | 3.36 | 2.72 | 19.51 | 14.22 | 113.16 | 74.24 |
| 0.25 | 1.45 | 1.31 | 8.41 | 6.81 | 48.77 | 35.55 | 282.91 | 185.61 |
| 0.5 | 2.90 | 2.61 | 16.82 | 13.62 | 97.55 | 71.11 | 565.82 | 371.23 |
| 0.75 | 4.35 | 3.92 | 25.23 | 20.43 | 146.33 | 106.67 | 848.73 | 556.85 |
| 1 | 5.80 | 5.22 | 33.64 | 27.24 | 195.11 | 142.23 | 1131.65 | 742.47 |
| 1.5 | 8.70 | 7.83 | 50.46 | 40.87 | 292.66 | 213.35 | 1697.47 | 1113.71 |
| 2 | 11.60 | 10.44 | 67.28 | 54.49 | 390.22 | 284.47 | 2263.29 | 1484.95 |
| 2.5 | 14.50 | 13.05 | 84.10 | 68.12 | 487.78 | 355.59 | 2829.12 | 1856.18 |
| 3 | 17.40 | 15.66 | 100.92 | 81.74 | 585.33 | 426.71 | 3394.94 | 2227.42 |
| 3.5 | 20.30 | 18.27 | 117.74 | 95.36 | 682.89 | 497.82 | 3960.77 | 2598.66 |

Table.1 SDC for different $\alpha$ and $\eta$ values

A.

| **Production function** | |
|---|---|
| Corn | $1.615+0.082n-0.0002n^2$ |
| Soybean | $1.88+0.0254\,p-0.0002p^2$ |
| Wheat | $1.752+0.055\,n-0.0003n^2$ |
| **N Balance Function** | |
| N Uptake coefficient for C-C | 0.73 |
| N Load coefficient C-C | 0.081 |
| Soybean N_fixing coefficient | Min (80,43.53*Yield) |
| N Uptake coefficient for C-S | 0.77 |
| N Load coefficient C-S | 0.072 |
| Wheat uptake coefficient | 0.81 |
| Wheat N Load coefficient | 0.061 |
| **Cost and Prices** | |
| Price of Corn ($/ton) | 159.74 |
| Price of Soybean($/ton) | 330.60 |
| Price of Wheat($/ton) | 146.97 |
| Price of Nitrogen Fertilizer($/kg) | 1.57 |
| Price of Phosphorus fertilizer($/kg) | 1.70 |
| Technology Cost for split N application ($/ha) | 25.00 |
| Technology Cost for cover crop ($/ha) | 110.00 |

B.

| **BMP** | **Corn-Corn** | **Corn-Soybean** | | **Corn-Soybean-Wheat** | | |
|---|---|---|---|---|---|---|
| **Technology** | **Corn** | **Corn** | **Soybean** | **Corn** | **Soybean** | **Wheat** |
| **Change in Crop Production** $(\boldsymbol{\beta} \times \mathbf{100})$ | | | | | | |
| Cons. Tillage | -0.01 | -0.01 | -0.02 | -0.01 | -0.03 | -0.01 |
| Cover Crops | -0.01 | -0.01 | -0.03 | -0.01 | -0.03 | -0.03 |
| N-Split | -0.02 | -0.02 | 0.00 | -0.03 | 0.00 | -0.01 |
| Buffer | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **N Loading by crop** $(\boldsymbol{\theta} \times \mathbf{100})$ | | | | | | |
| Cons. Tillage | -0.06 | -0.06 | -0.07 | -0.07 | -0.07 | -0.02 |
| Cover Crops | -0.07 | -0.07 | -0.05 | -0.06 | -0.06 | -0.07 |
| N-Split | -0.06 | -0.07 | -0.00 | -0.08 | -0.00 | -0.07 |
| Buffer | -0.32 | -0.32 | -0.32 | -0.32 | -0.32 | -0.32 |

**Table 2. Parameter used in the model**

| | **Private (Revenue-Input cost)** | **Ohio** |
|---|---|---|
| **Corn** | | |
| Yield (t/ha) | 9.84 | 10.27 |
| Fertilizer-N (Kg/ha) | 174.5 | 174.26 |
| Profit ($/ha) | 558.00 | 476.00 |
| **Soybean** | | |
| Yield (t/ha) | 2.68 | 3.63 |
| Fertilizer-P (Kg/ha) | 42 | 48 |
| Profit ($/ha) | 470 | 462 |
| **Wheat** | | |
| Yield (t/ha) | 4.15 | 5.01 |
| Fertilizer-N (Kg/ha) | 80.03 | 92.15 |
| Profit ($/ha) | 140.16 | 179.04 |

**Table 3. Comparison of baseline result with field crop enterprise budget-2009**

| | **Private (Revenue-Input cost)** | **Profit with internalized pollution cost** |
|---|---|---|
| **Corn-Soybean-Wheat** | | |
| Yield (t/ha) C | 9.64 | 6.15 |
| S | 2.81 | 2.20 |
| W | 4.03 | 2.50 |
| N load(kg/ha) | 12.87 | 6.63 |
| Fertilizer (Kg/ha) | 170.51 | 103.41 |
| DP value function ($/ha) | 7950 | 5163 |
| Reservoir-N (kg) | 11.77 | 6.03 |

**Table 4. Profit maximization with and without cost of pollution**

| | **Private (Revenue-Input cost)** | **Profit with internalized pollution cost** | **Technology Set-2** | **Technology Set-3** |
|---|---|---|---|---|
| Yield (t/ha) C<br>S<br>W | 9.64<br>2.81<br>4.03 | 6.15<br>2.20<br>2.50 | 8.72<br>2.41<br>3.07 | 9.04<br>2.35<br>3.80 |
| N load(kg/ha) | 12.87 | 6.63 | 7.25 | 7.03 |
| Fertilizer (Kg/ha) | 170.51 | 103.41 | 112.46 | 137.48 |
| Discounted profit ($/ha) | 7950 | 5163 | 5430 | 5940 |
| Reservoir-N (kg) | 11.77 | 6.03 | 6.53 | 6.33 |

**Table 5. Results after application of conservation technologies with current cultivation**

| | **Private (Revenue-Input cost)** | **Profit with internalized pollution cost** | **Technology Set-2** | **Technology Set-3** |
|---|---|---|---|---|
| Yield(t/ha) | 9.64 | 6.15 | 8.75 | 9.12 |
| N load(kg/ha) | 12.87 | 6.63 | 125.00 | 149.00 |
| Fertilizer (Kg/ha) | 170.51 | 103.41 | 9.50.00 | 11.02 |
| Discounted profit ($/ha) | 7950 | 5163 | 8037.00 | 8982.00 |
| Reservoir-N (kg) | 11.77 | 6.03 | 9.19 | 8.55 |

**Table 6. Results after application of conservation technologies with C-C rotation**

| | **Private (Revenue-Input cost)** | **Profit with internalized pollution cost** | **Technology Set-2** | **Technology Set-3** |
|---|---|---|---|---|
| Yield(t/ha) | 9.64 | 6.15 | 8.75 | 9.12 |
| N load(kg/ha) | 12.87 | 6.63 | 6.83 | 7.52 |
| Fertilizer (Kg/ha) | 170.51 | 103.41 | 132.04 | 137.16 |
| Discounted profit ($/ha) | 7950 | 5163 | 6075.00 | 6132.81 |
| Reservoir-N (kg) | 11.77 | 6.03 | 6.15 | 6.77 |

**Table 7. Results after application of conservation technologies with C-S rotation**