

# **Natural Resources at Risk: Water Quality and the Dead Zone in the Gulf of Mexico**

For presentation at the AERE Workshop, Jackson, WY June 2005.

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May 16, 2005

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# **Natural Resources at Risk: Water Quality and the Dead Zone in the Gulf of Mexico**

## **I. Introduction**

Water quality impairments in the Mississippi River system have been created over decades through fundamental alteration of the natural landscape via modern agriculture and urban settlement (Goolsby *et al.*). The significant “dead zone” or, more accurately, hypoxic zone in the Gulf of Mexico is the single most visible manifestation of this degradation. Hypoxia is a phenomenon that occurs where freshwater empties into lakes or oceans. The deposition of organic matter at the outlet produces an area where oxygen is depleted through the decomposition of this organic material, resulting in a hypoxic or dead zone, where few or no living organisms can survive. While naturally occurring, the size of the dead zone is now generally believed to be substantially more widespread than its historical size, with a major contributing factor being agricultural production in the Upper Mississippi River Basin (UMRB) where intensive agriculture dominates the landscape and delivers significant amounts of nutrients, particularly nitrates, to the Gulf.<sup>2</sup>

In addition to its significant contribution to the hypoxic problem in the Gulf of Mexico, agricultural activity in the UMRB has resulted in significant soil erosion and phosphorous deposition in local lakes and streams. In particular, lakes in this region contain some of the highest concentrations of phosphorous in the world (Downing, 2003) and, according to the US EPA over 1,200 stream segments and lakes in the region are listed as impaired (USEPA, 2003).

Thus, agricultural production in the UMRB contributes to two different water quality problems that are both related to nutrients: phosphorous and nitrogen. There are a number of abatement activities that agriculture can undertake that have been demonstrated to reduce either

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<sup>2</sup> Important scientific uncertainties as the complete cause of the dead zone remain. For example, a recent EPA report suggests that the limiting nutrient may be phosphorous rather than nitrogen. Regardless, it seems clear that significant reductions in one or both nutrients will be necessary if the size of the zone is to be notably reduced.

phosphorous (and erosion)<sup>3</sup> deposition and/or nitrate movement. Thus the characteristics of the source/externality relationships fit the definition of “correlated externalities” as proposed by Caplan and Silva (2005).

In this paper, we present a simple conceptual model that captures the key features of the local and regional water quality externalities generated by cropland agriculture in the UMRB. These key features can be summarized as follows:

1. Two externalities are generated by the production of a good (agricultural output),
2. One externality generates local damages (the damages do not extend beyond the local watershed) and the other generates regional damages (damages occur at a downstream location, not the local watershed),
3. Production is spatially distributed within the local watersheds and
  - a. the damages from each production unit vary from one another, and
  - b. they are non-separable from the choices of other production units in the same local watershed,
4. The abatement technology used to reduce the local damage also reduces the regional damage and vice versa. However, for simplicity we assume in the conceptual model that the latter is not the case, i.e., that abatement technology targeting the regional pollutant does not have local water quality benefits

Based on insights from the conceptual model, we present a simple two-part policy approach to address both the regional and local water quality problems designed with both efficiency and practicality considerations in mind. The policy combines a practice-based technology for local water quality control with a simple nitrogen trading framework across local

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<sup>3</sup> Note that phosphorous attaches to sediment whereas nitrogen is water soluble. Thus, phosphorous and soil erosion tend to be highly correlated, and phosphorous is generally the limiting nutrient in fresh water aquatic systems, whereas nitrates are more of a concern in coastal waters.

watersheds. This policy forms the basis for our empirical investigation of costs and ambient local and regional water quality changes.

Critical to the empirical work is the coupling of a watershed based model that captures the complex interactions between land use, conservation practices, land characteristics, and ambient water quality with economic models that predict the costs of adopting land use changes under various policy regimes. This integrated modeling framework incorporates the notable spatial heterogeneity in the region and integrates micro behavior and natural system responses over small units, rather than relying on typical agent behavior or average physical responses. The units of analysis employed in the system are the National Resources Inventory (NRI) sample points. There are over 110,000 such points in the UMRB, each representing a combination of weather, soil characteristics, crop choices, rotations, and other agro-ecological conditions, thus allowing us to retain the rich economic and environmental diversity of this managed ecosystem.

One critical question raised in the conceptual model and assessed in the empirical work is the degree to which a full blown watershed model is required in designing and implementing reasonably efficient policies. More specifically, we assess the extent to which policy design can be based on assumptions that transform the watershed problem into a simpler spatial model with constant and linear diffusion coefficients.

Before introducing the conceptual model in section III, we begin with a brief description of the UMRB, Gulf Hypoxia, and the abatement opportunities and technologies. Section III details the conceptual model, and section IV outlines the policy to be studied. The data and models used in the empirical analysis are described in section V, while VI presents results of the scenarios. We conclude with observations and proposed future work.

## II. Water Quality in the UMRB, Hypoxia in the Gulf, and Watershed Modeling Efforts

Figure 1 contains a map of the Upper Mississippi River Basin and its position in the central U.S. Cropland and pasture are the dominant land uses in the UMRB, which together are estimated to account for nearly 67% of the total area (NAS 2000). Nutrient inputs (nitrogen and phosphorous) to fertilize the land are the primary sources of nonpoint source pollution in the UMRB stream system. In fact, the nitrate load discharged from the mouth of the Mississippi River has been implicated as an important cause of the oxygen-depleted hypoxic zone, which had grown to nearly 20,000 km<sup>2</sup> in 1999 (Rabalais et al., 2002). Approximately 90% of the nitrate load to the Gulf is attributed to non-point sources and it has been estimated that the UMRB was the source of nearly 39% of the Mississippi nitrate load discharged to the Gulf between 1980 and 1996.

While nitrate loads are believed to be the primary limiting nutrient in the dead zone in the Gulf, phosphorous and sediment are the primary culprits of local water quality problems. There are a number of abatement activities that individual farmers can undertake to reduce sediment and phosphorous deposition. These conservation practices include conservation tillage (where residue from the previous year's crop is left on the ground to help reduce erosion), buffer strips, grassed waterways, as well as complete retirement of land from crop production in favor of other uses.<sup>4</sup> These practices also generally reduce the nitrate loading of a particular parcel as well. In addition, nitrogen loadings can be directly controlled by reducing the amount of application of nitrogen to the crop, either in the fall before planting or in the spring.

In the scientific literature, there are a large number of studies that assess the degree to which these various practices are effective in improving water quality (for example, Richards and

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<sup>4</sup> The Conservation Reserve Program (CRP) is a very large, federally funded program that makes direct payments to farmers to remove their land from active production and instead plant trees or other perennial ground cover.

Grabow 2003; Hussain et al. 1999; Baer et al. 2000). Further, there are numerous studies in the economics literature that examine agents' decisions to adopt these conservation practices, however, the environmental impacts of these practices are generally not evaluated. Sunding and Zilberman (2000) provide a review of the economics literature on farmers' adoption of conservation practices and new technologies in general. There are also some careful, small scale studies that consider the full link from proposed policy enactment to behavior change to environmental consequences (Khanna et al., Beaulieu et al.), but few have studied the issue at the scale we consider and none have explicitly studied the possible empirical trade-off between regional and local water quality and problems.

Several important modeling efforts have been undertaken with respect to the UMRB. First, Doering et al. (1999), analyzed the costs and benefits of implementing conservation policies in the UMRB as part of the assessment that provided the basis for the 2000 Hypoxia Action Plan. Their report was not watershed-based and its spatial units of analysis were aggregated regions in a mathematical programming model. More recently, this model has been modified to be watershed-based to study the possible co-benefits of conservation policies for water quality and greenhouse gas emission reductions (Greenhalgh and Sauer 2003). However, the model remains based on quite aggregate spatial units and is thus not well suited to policy assessments concerning local water quality or local vs. regional water quality tradeoffs. A second effort, by Wu et al. (2004) examined the impact of agricultural runoff from the UMRB by combining an economic model with a biophysical model that predicts changes in nutrients leaving the edge of a field. While such models have significant strength in studying local water quality, their use for assessing in-stream water quality is limited as they do not link field level changes to ambient water quality.

### III. Conceptual Model

We begin our presentation with a simple model of a correlated externality that preserves the key features of the interrelationships between hypoxia and the local water quality problem. In particular, we suppose there are  $J$  “upstream” sub-watersheds, each with a single location where local water quality is monitored (the exit point of the watershed). The local water quality at each of these monitoring points is affected by the abatement activities of the multiple production sources in the sub-watershed region. Production activities interact in a nonlinear way to produce the water quality concentrations measured at the exit of the sub-watershed. Moreover, we assume that abatement activities in sub-watersheds upstream of watershed  $j$  may also affect the water quality within the watershed.<sup>5</sup> Similarly, regional water quality, monitored at the exit point of the most downstream sub-watershed, is affected by the abatement activities at all sub-watersheds.

We order the watersheds such that watershed  $j$  is either located upstream of or parallel to watershed  $k$  if  $j$  is less than  $k$ . Let  $a_{ij}^l$  be the abatement activities that are focused primarily on local water quality at production source  $i$  of sub-watershed  $j$ , and let  $a_{ij}^r$  be the abatement activity targeted at regional water quality. To shorten notation, we define  $\mathbf{a}_j^l \equiv (a_1^l, a_2^l, \dots, a_{M_j}^l)$  and  $\mathbf{a}_j^r \equiv (a_1^r, a_2^r, \dots, a_{M_j}^r)$  where  $M_j$  is the number of production sources in sub-watershed  $j$ . We characterize the relationship between the abatement activities and the improvement in local water quality at sub-watershed  $j$  as:  $q_j = q_j(\mathbf{a}_j^l | q_1, \dots, q_{j-1})$  where the superscript  $l$  stands for local water quality. Similarly, the improvement in regional water quality is characterized as  $H = h(\mathbf{a}_1^l, \mathbf{a}_2^l, \dots, \mathbf{a}_j^l, \mathbf{a}_1^r, \mathbf{a}_2^r, \dots, \mathbf{a}_j^r)$ . Although both  $q_j(\bullet)$  and  $H(\bullet)$  are generally increasing in the abatement activities, this is not necessarily the case. The functions are very complicated and are

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<sup>5</sup> This does not change the central message of our analysis, as long as we assume that local communities will take actions to improve local water quality, and their actions will partially address regional water quality problems.

often only simulated by complex water quality assessment models. The cost function for taking the abatement activities is denoted as  $c_{ij}(a_{ij}^l, a_{ij}^r)$  and is assumed to be increasing in both arguments.

### III.1. First-best abatement activities to achieve given water quality goals

Suppose there are a set of local water quality improvement goals for the whole region and for each sub-watershed,  $\bar{H}$  and  $\bar{q}_j$  for  $j = 1, 2, \dots, J$ , respectively. Then the first-best abatement activities to achieve these goals can be solved from the following cost minimization problems.

$$(1) \quad \begin{aligned} & \text{Min}_{a_{ij}^l, a_{ij}^r} \sum_{j=1}^J \sum_{i=1}^{M_j} c_{ij}(a_{ij}^l, a_{ij}^r) \\ & \text{s.t. } \bar{q}_j \leq q_j(\mathbf{a}_j^l | q_1, \dots, q_{j-1}), j = 1, \dots, J, \\ & \quad \bar{h} \leq h(\mathbf{a}_1^l, \mathbf{a}_2^l, \dots, \mathbf{a}_J^l, \mathbf{a}_1^r, \mathbf{a}_2^r, \dots, \mathbf{a}_J^r). \end{aligned}$$

Assuming interior solutions and using  $\lambda_j$  and  $\lambda_h$  to denote the Lagrange multipliers for the  $J$  local water quality constraints and the single regional water quality constraint, we can characterize the solutions as follows. For optimal regional abatement activities, the condition is

$$(2) \quad \frac{\partial c_{ij}(\hat{a}_{ij}^l, \hat{a}_{ij}^r) / \partial a_{ij}^r}{\partial h(\hat{\mathbf{a}}_1^l, \hat{\mathbf{a}}_2^l, \dots, \hat{\mathbf{a}}_J^l, \hat{\mathbf{a}}_1^r, \hat{\mathbf{a}}_2^r, \dots, \hat{\mathbf{a}}_J^r) / \partial a_{ij}^r} = \hat{\lambda}_H, \text{ for all } i, j,$$

where hat indicates first best solutions. The condition indicates that the ratio between the marginal cost of taking regional abatement activities and the corresponding marginal benefit from improved regional water quality is equal for all parcels in all sub-watersheds. By contrast, the condition for optimal local abatement activities is

$$\left[ \frac{\partial c_{ij}(\hat{a}_{ij}^l, \hat{a}_{ij}^r)}{\partial \hat{a}_{ij}^l} - \lambda_h \frac{\partial h(\hat{a}_1^l, \hat{a}_2^l, \dots, \hat{a}_j^l, \hat{a}_1^r, \hat{a}_2^r, \dots, \hat{a}_j^r)}{\partial \hat{a}_{ij}^r} - \lambda_{j+1} \frac{\partial q_{j+1}(\hat{a}_{j+1}^l | q_1, \dots, q_j)}{\partial \hat{a}_{ij}^l} - \dots - \lambda_j \frac{\partial q_j(\hat{a}_j^l | q_1, \dots, q_{j-1})}{\partial \hat{a}_{ij}^l} \right]$$

(3)  $\bullet \frac{1}{\partial q_j(\hat{a}_j^l | q_1, \dots, q_{j-1}) / \partial \hat{a}_{ij}^l} = \hat{\lambda}_j,$

for  $i = 1, \dots, M_j$ ;  $j = 1, \dots, J$ .

This condition differs from (2) in two aspects. The first difference is the extra terms in the numerator which effectively reduces the marginal cost of local abatement activities by its marginal contribution in reducing regional water pollution and downstream water pollution. Second, the ratio on the left of (3) is only equalized within a sub-watershed. This is because, for parcels in different watersheds, their abatement activity levels depend on the stringency of water quality standards in the watersheds they are located in. In general, for parcels of the same characteristics (in terms of both cost and water quality control) but in different watersheds, the more stringent the standards are, the higher the abatement levels will be.

### III.2. A second-best setting—sequential abatement activities with permit trading

We have analyzed the social optimal abatement levels at each production source in each watershed in order to achieve some given water quality target. To implement these optimal choices, we have to assume that there is no coordination problem between local and regional water quality solutions. In reality, things are often more complicated. To move closer to what may happen in the real world, we analyze a situation where local water quality control has been implemented without regional water quality in mind. In particular, we examine policy implications when local abatement activities have already been set at  $\bar{a}_{ij}^l$ .

How effective  $\bar{a}_{ij}^l$  is at improving regional water quality determines how much more regional abatement activities are needed to meet regional water quality standard. There might be

two extremes: with the adoption of  $\bar{a}_{ij}^l$  the regional water quality goal is met and no measures are needed to improve regional water quality; or the adoption of  $\bar{a}_{ij}^l$  does not change regional water quality at all. How much  $\bar{a}_{ij}^l$  can contribute to regional water quality is an empirical question and will be assessed in our empirical analysis.

Denote the water quality improvement achieved by  $\bar{a}_{ij}^l$  as  $\bar{h}^0$ , that is

$$(4) \quad \bar{h}^0 \equiv h(\bar{\mathbf{a}}_1^l, \dots, \bar{\mathbf{a}}_J^l, 0, \dots, 0).$$

Then the difference, denoted as  $\Delta\bar{h}$ , between the regional water quality goal ( $\bar{h}$ ) and  $\bar{h}^0$  is the additional change needed to achieve the goal, that is,

$$(5) \quad \Delta\bar{h} \equiv \bar{h} - \bar{h}^0.$$

Suppose  $\Delta\bar{h} > 0$ , then, to achieve  $\Delta\bar{h}$  at the least cost, we can find the optimal regional abatement activities by solving the following problems given  $\bar{a}_{ij}^l$ ,

$$(6) \quad \begin{aligned} & \underset{\mathbf{a}_{ij}^r}{\text{Min}} \sum_{j=1}^J \sum_{i=1}^{M_j} c_{ij}(\bar{a}_{ij}^l, \mathbf{a}_{ij}^r) \\ & \text{s.t.} \quad \bar{h} \leq h(\bar{\mathbf{a}}_1^l, \bar{\mathbf{a}}_2^l, \dots, \bar{\mathbf{a}}_J^l, \mathbf{a}_1^r, \mathbf{a}_2^r, \dots, \mathbf{a}_J^r). \end{aligned}$$

The condition for regional abatement activities looks the same as that in the first-best case except that the local abatement levels are not optimally determined, that is,

$$(7) \quad \frac{\partial c_{ij}(\bar{a}_{ij}^l, \tilde{a}_{ij}^r) / \partial a_{ij}^r}{\partial h(\bar{\mathbf{a}}_1^l, \bar{\mathbf{a}}_2^l, \dots, \bar{\mathbf{a}}_J^l, \tilde{\mathbf{a}}_1^r, \tilde{\mathbf{a}}_2^r, \dots, \tilde{\mathbf{a}}_J^r) / \partial a_{ij}^r} = \tilde{\lambda}_H, \text{ for all } i, j,$$

The extent that the solutions from this condition,  $\tilde{a}_{ij}^r$ , differs from the first best solutions,  $\hat{a}_{ij}^r$ , depends on how  $\bar{a}_{ij}^l$  differs from its first-best counterpart,  $\hat{a}_{ij}^l$ .

Suppose the pollutant (e.g. nitrogen application) that is relevant for regional water quality can be measured for each sub-watershed and denote this measurement as  $h_j$ , then the regional water quality function can be modified as

$$(8) \quad h = \tilde{h}(h_1, h_2, \dots, h_J).$$

The additional water quality improvement ( $\Delta \bar{h}$ ), e.g., in terms of nutrient reduction, can then be allocated to each sub-watershed as long as

$$(9) \quad \Delta \bar{h} = \tilde{h}(\Delta \bar{h}_1, \Delta \bar{h}_2, \dots, \Delta \bar{h}_J).$$

where  $\Delta \bar{h}_j$  is the nutrient reduction allocated to sub-watershed  $j$ . After the allocation, firms will be allowed to trade with each other. Let  $t_{jk}$  be the trading ratio between watershed  $j$  and  $k$ . More specifically, suppose  $t_{jk}=3$ , then three units of reduction in  $j$  is only worth 1 unit of reduction in  $k$ . Let  $p_j$  and  $y_j$  be the price and quantity of permits traded. Then, given,  $\bar{a}_j^l$ , in order to minimize cost of achieving  $\Delta \bar{h}_j$ , watershed  $j$  can solve the following problem

$$(10) \quad \begin{aligned} \text{Min}_{a_{ij}^r, y_k, y_j} & \sum_{i=1}^{M_j} c_{ij}(\bar{a}_{ij}^l, a_{ij}^r) + \sum_{k \neq j, k=1}^J y_k p_k - y_j p_j \\ \text{s.t.} & \Delta \bar{h}_j \leq \left[ h_j(\bar{\mathbf{a}}_j^l, \mathbf{a}_j^r) - h_j(\bar{\mathbf{a}}_j^l, \mathbf{0}) \right] + \sum_{k \neq j, k=1}^J t_{jk} y_k - y_j. \end{aligned}$$

The total cost is the cost of abatement activities plus the net cost of buying (selling) permits.

Similarly, the constraint is that that allocated nutrient reduction target must be achieved through abatement or permits net permits bought (sold) adjusted by trading ratios. In equilibrium for the permit trading market, we have

$$(11) \quad \frac{\partial c_{ij}(\bar{a}_{ij}^l, a_{ij}^r) / \partial a_{ij}^r}{\partial h_j(\bar{\mathbf{a}}_j^l, \mathbf{a}_j^r) / \partial a_{ij}^r} = \hat{\lambda}_j = p_j$$

$$(12) \quad \frac{P_j}{P_k} = t_{jk},$$

that is, the ratio of marginal cost over marginal benefit of regional abatement activities is equal across all sites in sub-watershed j, and the ratio is equal to the permit price for nutrient reduction in watershed j. The permit trading ratio is equal to the price ratios between any two sub-watersheds.

Denote the nutrient reduction actually achieved after trading, as  $\Delta h'_j$ , then the regional water quality actually achieved after trading will be

$$(13) \quad \Delta \bar{h}' = \tilde{h}(\Delta h'_1, \Delta h'_2, \dots, \Delta h'_j).$$

One major goal of this study is to assess the difference between  $\Delta \bar{h}$  as determined by (9) and  $\Delta \bar{h}'$  as determined by (13). When the marginal contribution of each sub-watershed is linear, equation (9) can be rewritten as

$$(14) \quad \Delta \bar{h} = d_1 \Delta \bar{h}_1 + d_2 \Delta \bar{h}_2 + \dots + d_j \Delta \bar{h}_j,$$

where  $d_j$  is the transferring coefficient from sub-watershed j to the outlet where regional water quality is measured.<sup>6</sup> In this case, if trading ratios ( $t_{jk}$ ) are based on the transferring coefficients ( $d_j$ ), then it can be shown that  $\Delta \bar{h}$  and  $\Delta \bar{h}'$  would be the same. However, when  $d_j$ 's are only approximate, it is interesting to know how this approximation affects the eventual policy outcomes in terms of cost incurred and benefit achieved. It is well known in the permit trading literature that under many circumstances the initial permit distribution has no efficiency consequences: given any initial distribution, firms will trade and achieve the environmental

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<sup>6</sup> For uniformly mixed pollutants like carbon dioxide, (14) holds with  $d_j = 1$  for all j.

target at the lowest cost. This result will also be assessed in our empirical analysis for water quality improvement.

#### **IV. Description of Policies as Applied to the UMRB**

Based on the above analysis, we propose and assess a far reaching policy that considers both local and regional water quality. To do so, we begin by evaluating the effects of abatement activities focused on local water quality by comparing the results of two scenarios. In the first one, no action is taken. In the second one, sound conservation practices are taken across the whole region. We then analyze several scenarios that are designed to examine several issues that arise in the implementation of nutrient trading for regional water quality improvement.

In sum, there are two levels of the policy:

1. Local water quality control. Local control boards set phosphorous/sediment standards and devise BMPS, NPS trading, or other approach to meet standards. The set of practices we use is based on the potential environmental impact as captured by several indicators, such as proximity to a stream, an erodibility index, and slope. The set of practices chosen is broad and includes terraces, contouring, grassed waterways, conservation tillage, and land set-aside. While the optimal set of conservation practices and their location in the landscape is the focus of major ongoing work in ecology and economics, we employ a set of practices and rules for “placing” them in the landscape jointly derived with the Iowa Department of Natural Resources for a project on meeting water quality goals for the state of Iowa. Thus, while this set of practices, like any, is arbitrary, it is a set that has been designed in conjunction with a state environmental agency with an eye towards both efficiency and reasonableness. In this vein, the set of practices could be considered akin to the efficiency based CAC policies that have been implemented in a number of cases (Oates, Portney, and McGartland).

While it may be easiest to think of this set of practices as being Command And Control (CAC), note that there is no reason that they must be implemented in such a fashion: they could also be induced by taxation, conservation subsidies (such as through the Conservation Security Program established in the 2002 farm bill), trading, or any other regulatory approach. The specific algorithm used to identify practices and their location is provided in Appendix 1.

2. Dead Zone control. The focus here is nitrogen and water quality in the Gulf. On the basis of the local water quality control policy (taken as given), reductions in N loading are computed and the necessary additional reduction in N to meet H goals are determined. The dead zone control board allocates N reduction to the local watersheds and then allows trading based on linearized, approximate trading ratio.

## **V. Data and Models**

To consider the costs and water quality consequences of the two-step policy we link a watershed based model with economic models and data on the costs of adopting conservation practices. The basic data for each model comes from the 1997 USDA National Resources Inventory (NRI) database (Nusser and Goebel 1997; <http://www.nrcs.usda.gov/technical/NRI/>). The NRI is a statistically based database that collects and reports land use information such as soil properties, landscape features, cropping histories, and conservation practices across the entire U.S. There are roughly 110,000 NRI sample points in the UMRB, each representing an area ranging in size from a few hundred to several thousand hectares. Data from the NRI is augmented with information from other sources including the 1990-95 Cropping Practices Survey (CPS) ([http://usda.mannlib.cornell.edu/usda/ess\\_entry.html](http://usda.mannlib.cornell.edu/usda/ess_entry.html)), data from local weather stations (Santhi, 2001), and detailed soil layer data (Baumer et al. (1994)). Using an NRI point as the basic unit of analysis provides the natural spatial linkage upon which to integrate the

watershed and economic models. For space considerations, we provide brief overviews of the two model components and direct interested readers to

<http://www.card.iastate.edu/environment/water/> for more information.

In the economic model, we assume that a landowner (farmer) will choose the land use and set of conservation practices for his land that offers the highest returns. Some conservation practices, such as conservation tillage may actually improve profitability under some combinations of weather and soil conditions and thus some farmers adopt even without regulation or financial inducements. However, other practices, such as buffers, terraces, and grassed waterways have no offsetting profitability gains and therefore generally require inducements for farmers to adopt. Complete retirement of land from production is likewise quite costly.

For purposes of policy assessment, we need estimates of the opportunity cost of adopting each abatement activity (conservation practice) on each parcel. For the case of conservation tillage, we use an econometrically estimated discrete choice adoption model for the UMRB and various sources for the costs of other conservation practices such as buffer strips, terracing, contour farming, and others (details can be found in Kling et al. 2005). The cost of nutrient reduction is largely based on the relevant existing literature.

The economic model is linked to a watershed-level hydrological model, the Soil and Watershed Assessment Tool (SWAT). SWAT is a conceptual, physically based, long-term continuous watershed scale simulation model that operates on a daily time. In SWAT, a watershed is divided into multiple subwatersheds, which are then further subdivided into Hydrologic Response Units (HRUs) that consist of homogeneous land use, management, and soil characteristics. Non-point-source loadings from each HRU are summed and the resulting loads

are routed through channels, ponds, and/or reservoirs to the watershed outlet. Key components of SWAT include hydrology, plant growth, erosion, nutrient transport and transformation, pesticide transport, and management practices. A number of studies have used the SWAT model in the local watersheds within the UMRB including work by Keith et al. 2002; Gassman et al. 2002; Saleh et al. 2002; Gassman et al. 2003a, Jha et al. 2004, Jha et al. 2003a; Jha et al. 2003b). In addition, SWAT has been applied to the entire UMRB (Arnold et al. (1999), Arnold et al. (2000), Gassman et al. 2003b) and comparisons of SWAT flow and sediment loss predictions compared favorably with measured data for two major UMRB river subsystems (Jha et al. 2003c) as have flow comparisons at Grafton, IL, the endpoint of the UMRB watershed.

In our hydrological analysis, the UMRB is subdivided into 131 subwatersheds, which correspond to the United States Geological Survey (USGS) 8-digit Hydrological Unit Codes (HUCs). For the purposes of the nutrient trading analysis, we group these watersheds into 14 larger watersheds, which correspond to 4-digit HUCs, and we take each of the 14 larger subwatershed as one of the policy units for the local water quality policy<sup>7</sup>. This allows us to analyze the policies with a relatively small number of coefficients. Figure 2 details their location, and their position in relation to the main stem of the Mississippi (highlighted in darker blue). The figure makes apparent that the watershed has a substantially linear structure in terms of these large subwatersheds. This influences the way the transferring coefficients  $d_j$  are calculated.

## **VI. Empirical Results and Discussion**

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<sup>7</sup> It is important to keep in mind that the subwatersheds are themselves composed of several watersheds. A nutrient trading policy, for example, could be set up within each of the 14 subwatersheds.

Before we can assess the changes in nutrient loadings resulting from potential implementation of the two policy levels outlined above, we must first establish the baseline levels land use, and pollutant loads. Using the data sources outlined in the previous section, summary information concerning the baseline land uses, sediment, nitrates and phosphorous loads are presented in Table 1. Data is summarized for each of the 14 sub-watersheds in the UMRB. The second and third columns of the table indicate the total area of the sub watershed and the number of acres in agricultural cropland as reported in the 1997 NRI. Also reported (in column four) is the area that is planted in corn or wheat as this is the acreage that is primarily subject to nitrogen application and therefore is the most relevant for the nitrate abatement technology applications (N reductions). The remainder of the table presents estimates of the baselines loads at the outlet of the sub watershed of the three primary pollutant, sediment, nitrates, and phosphorous resulting from application of the SWAT model to the UMRB.

For each pollutant, the loading into the reach column indicates the amount of pollutant entering the waterbodies in the sub-watershed. In contrast, the loading out of the reach column indicates the amount of each pollutant measured leaving the watershed. The latter measure most closely approximates the notion of ambient pollution measures, assuming that the point of measurement interest occurs at the outlet of each watershed. Of significant import is the fact that this outlet quantity also represents the contribution of sub-watershed X to the pollution load of the downstream watershed, together with the contributions of all the watersheds upstream of X, as indicated in the schematic in Figure 2. Note that the contributions of upstream watersheds are not simply a sum of the loads at each reach. The hydrology of the watershed in terms of its river structure, channel depth and width, slope and so on, together with the weather and level of pollutants entering the stream will affect the amount of pollutants carried downstream.

In the first level of the policy --- the local water quality control component --- we assume that a local control board in each of the fourteen sub-watersheds implements a strategy to achieve the implementation of the set of sound conservation practices discussed above and described in detail in appendix 1. While we do not explicitly model the method by which this implementation is achieved in this paper, we note that a variety of CAC requirements or subsidies have been used to induce the adoption of conservation practices in agriculture in the past and/or under current programs.

Table 2 will report summary results of the local water quality control policy, assuming that no regional (hypoxic zone) control related to nitrogen management has been undertaken. Columns 1 and 2 will repeat the information on watershed number and area to provide context for the land use changes. In column 3, we will report the acreage affected by one or more of the conservation practices described in the Sound Conservation Practices policy. The percentage change in treated acreage is reported in parentheses under each acreage figure. The next six columns will report the changes in pollutant loads as predicted by the SWAT model. The final column of the table will provide an estimate of the costs associated with implementing the sound conservation practices scenario in each of the sub regions. Note that these are estimates of the opportunity cost to landowners and farmers of adopting these practices, they do not include program costs, any possible transfer payments, or transactions or enforcement costs associated with implementation.

The results are striking. (ok, we hope they are at least interesting. We'll describe them here when the model runs are built and complete!)

Based on the results of the local water quality control policy, the Dead Zone Control Board will decide on the total amount of nitrate reduction needed from the UMRB and allocate these

reductions across the local control boards. As described earlier, the Dead Zone Board will allow sub regions to trade amongst themselves, based on the trading ratio that is specified by the Dead Zone Board.

For purposes of considering this scenario, we assume that the Board is interested in achieving a 40% reduction in nitrate contributions from the UMRB as measured at the outlet of the UMRB which coincides with the outlet of sub watershed 7140. This target of 40% comes from the hypoxic zone task force and is the recommendation most commonly considered in policy discussion regarding nitrogen reductions in the UMRB. Given that the sound conservation practices implemented in the local water quality control scenario has already achieved a XX% reduction in nitrate at the outlet of 7140, this means that the Dead Zone Control Board would like to achieve an additional XX% with its nitrate management trading regulations.

To implement the policy, the Board must announce a nitrate allocation to each sub watershed as well as the matrix of trading coefficients. In lieu of a completely arbitrary set of trading ratios, we assume that the Dead Zone Control Board constructs linear approximations to these ratios using the SWAT model. To do so, a series of 14 SWAT runs are being undertaken where the amount of nitrate applied in each sub watershed is reduced by XX%. Based on each run, we compute the change in nitrogen reductions at each of the downstream watersheds and convert it to a linear diffusion coefficient.

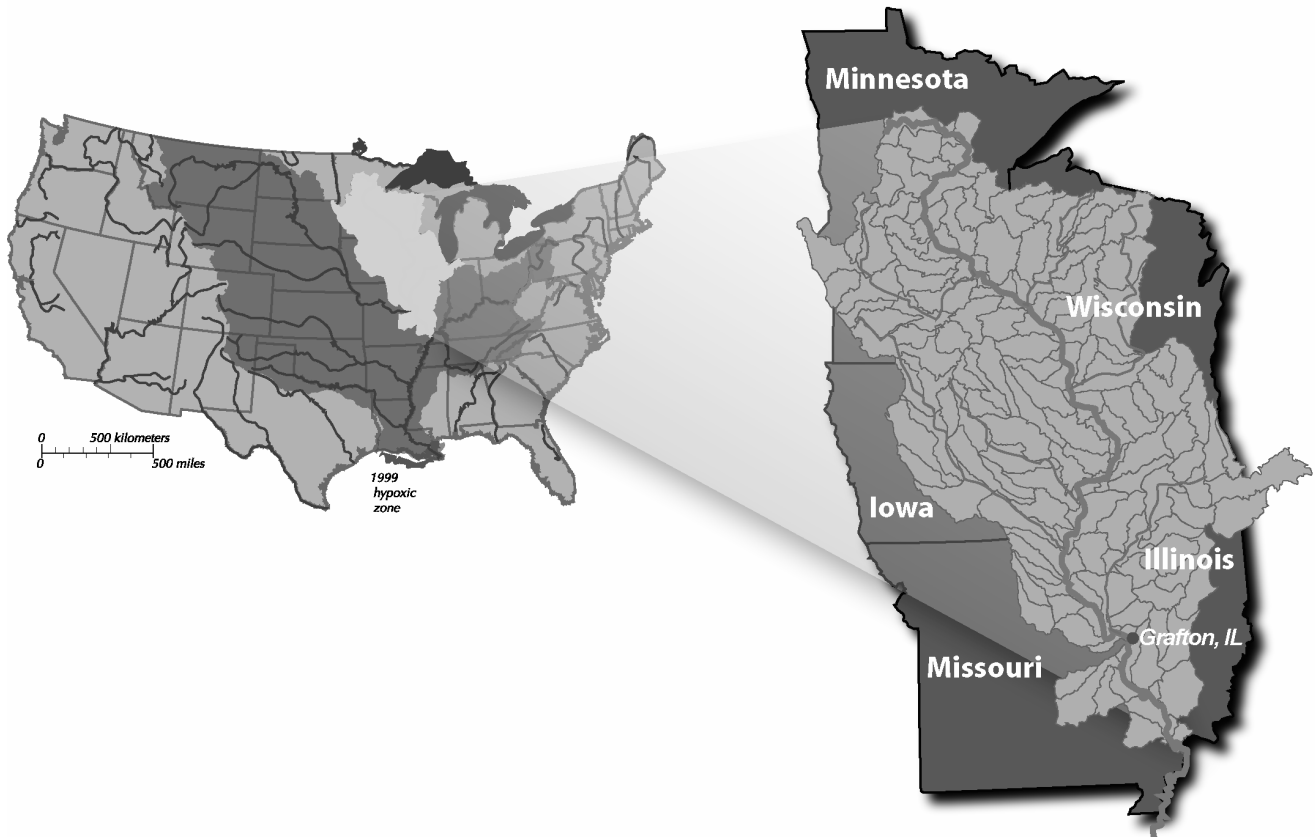
The resulting set of approximate linear diffusion coefficients will be reported in Table 3. We assume initially that the Dead Zone Control Board requires each sub watershed to reduce its nitrate applications by XX%. Again, we do not model the specific method by which each watershed achieves such a reduction - permits limiting the amount of nitrate sold in the region or

taxes on nitrogen fertilizer are two possibilities. Table 4 will contain the summary results of the trading scenario.

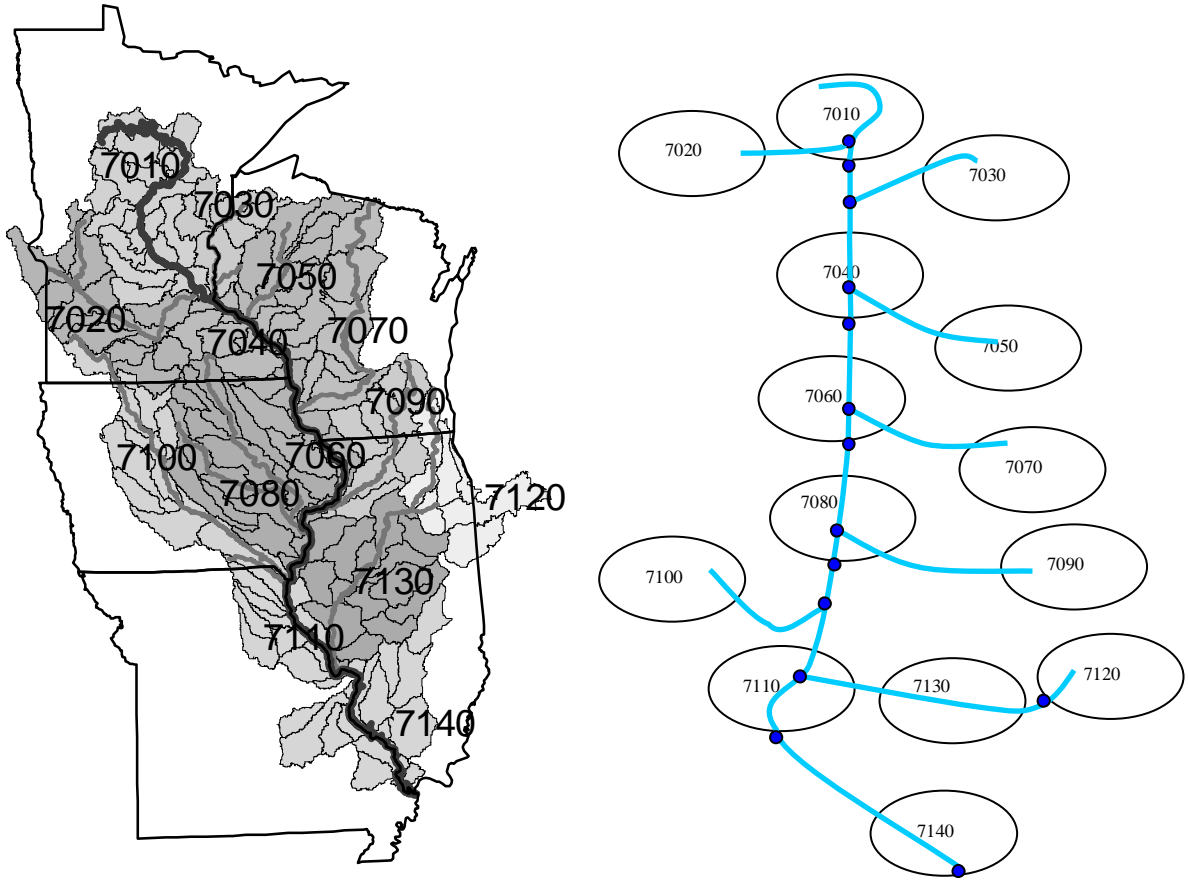
### **Final Remarks**

This paper has taken a first stab at an incredibly complex, politically charged, and massive environmental problem: the dead zone in the Gulf of Mexico and its relationship to local water quality in the Upper Mississippi River Basin. In addition to all of the well-known problems related to the efficient control of diffuse, nonpoint source pollution, this problem is also inherently interwoven with a variety of other social and economic concerns related to large scale changes in farming practices, ownership, and quality of life issues in the Midwestern region of the country.

**Figure 1. The Upper Mississippi River Basin and its 131 U.S. Geological Survey 8-digit watersheds.**



**Figure 2- The Upper Mississippi River Basin, its 14 U.S. Geological Survey 4-digit watersheds and a schematic of the watershed structure.**



In the schematic, the blue dots represent the outlets of the watersheds. When the outlet is at an intersection with another river, it shows by having two incoming rivers. When there are two incoming rivers, SWAT can calculate both what is happening in the water because of all the upstream effects and what is happening just because of the contribution of the single new watershed.

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## Appendix 1: Sound Conservation Practices

In concert with the Iowa Department of Natural Resources, conservation practices were identified on the basis of the physical characteristics of the agricultural land. The practices analyzed include grassed waterways, terraces, strip cropping, contouring, conservation tillage, land set-aside, and nutrient management strategies. The following steps identify the sets of practices and the selection criteria.

**Step 1.** Retire all cropland within ( $\leq$ ) 100 ft. of a waterway, placing it in CRP. CRP selection can override any previous conservation practice in place; i.e., terraces, contouring, strip cropping, and grassed waterways.

**Step 2.** Retire additional land to reach a 10% total land retirement figure within each state. This additional land is chosen by beginning with the acreage with the highest Erosion Index until the 10% figure is reached. Points are selected until the next point's area would exceed the 10% criteria.

**Step 3.** Terraces. For the cropland remaining after Steps 1 and 2, terrace all cropland with slopes above 7% or above 5% (this varied by region). This land is also placed in no till or conservation tillage --- see step 6. This can override contouring and strip cropping, but not grassed waterways.

**Step 4.** Contours. Implement contouring on all cropland not covered under Steps 1-3 with slopes above 4%. We do not put contours on baseline areas that were in grassed waterways, terraces, strip cropping, or existing contours.

**Step 5.** Grassed Waterways (GW). For all land not covered under Steps 1-3, and with slopes of 2% or greater (i.e., cropland with slopes from 2 to 7% in some regions and 2 to 5% in others), place 2% of the cropland in grassed waterways. In modeling the benefits of grassed waterways, assume only 50% of the parcel area with a grassed waterway is benefited by it. Do not override terraces, strip cropping, contours, or existing grassed waterways.

**Step 6.** Conservation/no till. For all cropland with slopes of 2% or greater that are not retired (Steps 1-2), and not already in conservation tillage, assume 20% of each 8-digit HUC will be in no till and 80% in conservation tillage. Thus all working cropland with slopes over 2% will be in conservation or no till. Finally, note that the term conservation tillage represents tillage that leaves over 30% residue and no till is used for the tillage practices that leave over 60% residue. Within each 8-digit HUC, points are randomly selected for no till until the next point's area would exceed the 20% criteria, and the remaining are designated as conservation tillage.



**Table 1: Upper Mississippi River Basin Baseline - Area and Pollution Loadings<sup>a</sup>**

| Watershed | Area<br>Km <sup>2</sup> | Area in<br>agricultural<br>uses <sup>b</sup> | Area in<br>corn or<br>wheat <sup>c</sup> | Sediment<br>load into<br>the<br>watershed | Sediment<br>load out of<br>the<br>watershed | Nitrates<br>load into<br>the<br>watershed | Nitrates<br>load out<br>of the<br>watershed | Total P<br>load into<br>the<br>watershed | Total P<br>load out<br>of the<br>watershed |
|-----------|-------------------------|----------------------------------------------|------------------------------------------|-------------------------------------------|---------------------------------------------|-------------------------------------------|---------------------------------------------|------------------------------------------|--------------------------------------------|
| 7010      | 52,189                  | 13,006                                       | 6,810                                    | 3,880                                     | 3,857                                       | 20,549                                    | 20,479                                      | 9,743                                    | 9,745                                      |
| 7020      | 43,719                  | 34,922                                       | 22,623                                   | 4,671                                     | 2,879                                       | 10,580                                    | 10,347                                      | 7,857                                    | 7,848                                      |
| 7030      | 20,066                  | 2,911                                        | 1,435                                    | 830                                       | 269                                         | 3,179                                     | 3,136                                       | 508                                      | 512                                        |
| 7040      | 27,916                  | 14,828                                       | 6,752                                    | 10,831                                    | 10,067                                      | 41,450                                    | 41,261                                      | 15,404                                   | 15,418                                     |
| 7050      | 24,680                  | 4,816                                        | 2,170                                    | 1,572                                     | 790                                         | 8,396                                     | 8,312                                       | 876                                      | 882                                        |
| 7060      | 22,168                  | 14,941                                       | 6,856                                    | 22,454                                    | 18,636                                      | 66,372                                    | 66,133                                      | 24,103                                   | 24,110                                     |
| 7070      | 30,802                  | 7,726                                        | 2,989                                    | 2,579                                     | 845                                         | 10,946                                    | 10,758                                      | 3,449                                    | 3,431                                      |
| 7080      | 59,444                  | 49,267                                       | 23,272                                   | 36,287                                    | 32,357                                      | 133,272                                   | 132,389                                     | 53,517                                   | 53,501                                     |
| 7090      | 28,351                  | 19,879                                       | 11,545                                   | 11,741                                    | 3,158                                       | 23,372                                    | 22,800                                      | 10,216                                   | 10,261                                     |
| 7100      | 37,550                  | 29,079                                       | 12,401                                   | 3,857                                     | 1,000                                       | 22,398                                    | 22,152                                      | 9,550                                    | 9,417                                      |
| 7110      | 26,043                  | 15,635                                       | 10,686                                   | 53,617                                    | 50,083                                      | 250,222                                   | 249,944                                     | 92,589                                   | 92,561                                     |
| 7120      | 28,286                  | 16,830                                       | 9,899                                    | 7,151                                     | 3,839                                       | 43,066                                    | 42,184                                      | 6,370                                    | 6,402                                      |
| 7130      | 46,338                  | 34,937                                       | 21,176                                   | 22,401                                    | 17,226                                      | 83,056                                    | 81,556                                      | 23,299                                   | 23,318                                     |
| 7140      | 44,169                  | 18,323                                       | 17,429                                   | 61,656                                    | 56,567                                      | 292,222                                   | 291,389                                     | 101,144                                  | 101,122                                    |

- a. Loads are measured in thousand of tons, 18 year averages.
- b. Area is based on 1997 data and includes land in the Conservation Reserve Program.
- c. These are the areas that receive nitrogen fertilizer.