

# ***Nutrient Biocomplexity in a National Watershed: The Ohio River Basin***

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## ***Statement of the problem***

“Biocomplexity refers to the dynamic web of often surprising interrelationships that arise when components of the global ecosystem – biological, physical, chemical, and the human dimension – interact. The concept of biocomplexity stresses the richness of biological systems and their capacity for adaptation and self-organizing behavior”<sup>1</sup>. The study of biocomplexity is a rapidly developing area of research that seeks to better understand the emergent properties of ecosystems and how they may be affected as underlying mechanisms or external forcing functions change<sup>2</sup>.

In many ecosystems on land and sea, the supply of nitrogen is a key factor controlling the nature and diversity of plant life, the population dynamics of both grazing animals and their predators, and vital ecological processes such as plant productivity and the cycling of carbon and soil minerals. This is true not only in wild or unmanaged systems but in most croplands and forestry plantations as well. Excessive nitrogen additions can pollute ecosystems (the so-called “nutrient pollution”) and alter both their ecological functioning and the living communities they support.

Over the last century, runoff from farms and cities, along with land cover and land use changes, has drastically altered the global nitrogen cycle. In fact, humans have already doubled the rate of nitrogen entering the land-based N (nitrogen) cycle, and that rate is continuing to climb<sup>3</sup>. This human-driven global change is having serious impacts on ecosystems around the world because N is essential to living organisms and its availability plays a crucial role in the organization and functioning of natural systems. Figure 1 shows the main sources of nutrient pollutants to aquatic ecosystems.

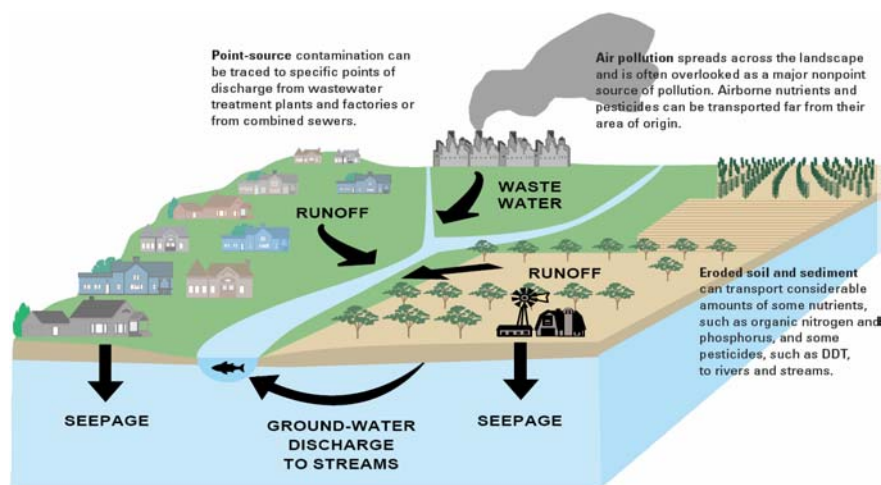
Most of the human activities responsible for the increase in global nitrogen are local in scale, from the production and use of nitrogen fertilizers to the burning of fossil fuels in automobiles, power generation plants, and industries. However, human activities have not only increased the supply but enhanced the global movement of various forms of nitrogen through air and water. Because of this increased mobility, excess nitrogen from human activities has serious and long-term environmental consequences for large regions of the Earth<sup>3</sup>.

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<sup>1</sup> NSF 01-34 “Biocomplexity in the Environment” (<http://www.nsf.gov/pubs/2001/nsf0134/nsf0134.htm>).

<sup>2</sup> USGS Fact Sheet 2004-3124 (March 2006) “Nutrient Controls on Biocomplexity of Mangrove Ecosystems”

<sup>3</sup> ESA Issues in Ecology #1 (1997) “Human Alteration of the Global Nitrogen Cycle: Causes and Consequences”.



**Figure 1. Sources of nutrient pollutants to aquatic systems**

In aquatic ecosystems, nutrient pollution causes a wide range of ecological problems, including toxic algal blooms, loss of oxygen, fish kills, disruption of food webs, and loss of biodiversity (including species important to commercial and sport fisheries and shellfish industries).

Human health problems have also been associated with nutrient pollution<sup>4</sup>. Some of the algal species that take advantage of excess nutrient availability produce powerful toxins that can harm humans and animals<sup>5</sup>. Ingested nitrites and nitrates also have a potential role in developing cancers of the digestive tract through their contribution to the formation of nitrosamines<sup>6</sup>. They have also a determinant role in infant methemoglobinemia<sup>7</sup>, and evidence suggests that ingesting nitrogen compounds might result in mutagenicity, teratogenicity and birth defects<sup>8</sup>, contribute to the risks of non-Hodgkin's lymphoma and bladder and ovarian cancers<sup>4</sup>, play a role in the etiology of insulin-dependent diabetes mellitus<sup>9</sup> and in the development of thyroid hypertrophy<sup>10</sup>, or cause spontaneous abortions<sup>11</sup>, coronary heart disease<sup>12</sup> and respiratory tract infections<sup>13</sup>.

The proposed research program will address those ecological and societal issues on the Ohio River Basin, one of the nation's regional watersheds.

<sup>4</sup> Environ. Intern. 32:831-849. "Ecological & toxicological effects of inorganic nitrogen pollution in aquatic ecosystems".

<sup>5</sup> Annals N.Y. Acad. Sci. 740:77-94. "Emerging diseases associated with seafood toxins and other water-borne agents".

<sup>6</sup> Intern. J. Cancer 80:852-856. "Risk of colorectal and other gastro-intestinal cancers after exposure to N-compounds".

<sup>7</sup> Environ. Health Perspect. 108:675-678. "Blue babies and nitrate-contaminated well water".

<sup>8</sup> Environ. Health Perspect. 114:320-327. "A review of nitrates in drinking water: Maternal exposure and adverse reproductive and developmental outcomes".

<sup>9</sup> Diabetologia 40:550-556. "Incidence of childhood diabetes mellitus is associated with nitrate in drinking water".

<sup>10</sup> Toxicology Letters 72:365-374. "Consumption of drinking-water with high nitrate levels causes thyroid hypertrophy".

<sup>11</sup> J. Occupational and Environ. Medicine 43:377-383. "Agricultural contamination of groundwater as a possible risk factor for growth restriction or prematurity".

<sup>12</sup> Epidemiology 12:S84 457. "Association of nitrate levels in municipal drinking water and diet with risk of coronary heart disease mortality: The Iowa women's health study".

## ***The Ohio River Basin***

The Ohio River Basin, whose watershed covers a drainage area of 203,940 square miles, includes parts of Illinois, Indiana, Ohio, Pennsylvania, New York, Kentucky, Tennessee, North Carolina, Virginia, West Virginia, and Maryland (see Fig. 2). The population of the Basin is over 25 million (about 10% of the U.S. population, and have experienced a 20% increase since 1970. This population increase is a result of increasing growth of the economic activity and urbanization. All types of economic activities can be seen within the Basin, from mining and agriculture to manufacturing and commerce. There are 20 dams and 49 power generating facilities along the Ohio River, with a combined capacity in excess of 6% of the total U.S. generating capacity. The river is also an important link in the trade network, as well as the main source of drinking water to more than four million people.



**Figure 2. The Ohio River Basin includes parts of 11 states**

The geology and land use within the Basin are varied and complex. The Appalachian Plateau in the eastern portion of the Basin is characterized by a rugged topography and extensive forest cover. The Central Lowlands, in the north-western third of the Basin, mark the southern limit of the massive ice cap that covered North America up to about 20,000 years ago. This flat area, the result of several glaciations, contains some of the richest agricultural lands in the Basin. The Interior Low Plateau, in the south-western third of the Basin, is dominated by limestone rock and a rolling terrain. The hydrology of the Ohio River Basin is also very unique. Most of the Basin is drained by tributaries, with less than 5% of the basin runoff draining directly into the main stem.

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<sup>13</sup> Environ. Health Perspect. 108:363-366. "Recurrent acute respiratory tract infections in areas with high nitrate concentrations in drinking water".

Much of the area of the Basin is occupied by agriculture. The use of nitrogen fertilizer has led to increased agricultural yields and economic development, but has also resulted in increased fluxes of nitrogen compounds to both surface and ground water. Research have shown that, on average, only 30% of the fertilizer and feed input to farming systems is output in crops and animal produce; the rest is stored in soils or is transported to streams and groundwater<sup>14</sup>. The existing N budgets for the Ohio River Basin indicate that, between 1989 and 1993, it had almost 2 million tons of N stored<sup>15</sup>. This storage, however, is only temporary, as leaching of nitrate during recharge and export to groundwater and surface water is the ultimate fate of this excess nitrogen. Current models are unable to predict adequately the future of this excess nitrogen, especially if we are to consider future changes in temperature and humidity as a result of climate change.

Recent research has shown much indirect evidence of N-storage, particularly in agriculturally-dominated areas<sup>16</sup>. Furthermore, base-flow N concentrations (e.g., during dry periods) are often much greater than during storm-flow conditions (e.g., during the wet season). Thus, it appears that the flushing of excess N is controlled by local hydrology (including hydrologic variability and landscape topography). Steep slopes has been shown to produce low N-input rates to streams but in flat, planar watersheds, the rate of N input to the aquatic regime showed short flushing times and sharp pulses<sup>17</sup>. The understanding of this hydrologic control of riverine N loading and transport in an anthropogenically affected watershed, such as the Ohio River Basin, is a central goal of this research program. We will use both hydrological (wet/dry variability and landscape topography) and biogeochemical (nutrients) datasets to create a model of the nutrient dynamics in the Basin.

### ***Objectives and expected significance of the work***

Scientific questions to be answered by this research program are: (1) How historical changes in land use have affected the hydrology of the Ohio River Basin? (2) How these changes have affected (are affecting) water quality (nutrient cycling) and water availability (both surface and ground water) within the basin? (3) How will the watershed respond to climate extremes (in humidity and temperature) resulting from global warming? (4) What will the impacts be for agricultural, industrial and urban activities (of changing hydrology and nutrient loading)? (5) What preventative and adaptive measures can be put in place to mitigate such impacts?

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<sup>14</sup> Sharpley et al., 2003. U.S. Department of Agriculture. Agricultural Research Service publication ARS-149. 44 pp.

<sup>15</sup> Environ. & Engineering Geoscience 7:251-265. "Nitrogen Budget in the Upper Mississippi River Watershed"

<sup>16</sup> Groundwater 39:290-299. "Relating N sources and aquifer susceptibility to nitrate in shallow ground waters of the US"

<sup>17</sup> Wat. Resources Res. 34:3105-3120. "Export of N from catchments within a temperate forest"

## Relation of proposed work to present state of knowledge

Although numerous large (such as USGS-NAWQA<sup>18</sup> and various LTER sites<sup>19</sup>) and small (single-investigator) programs have attempted to relate hydrologic processes to biogeochemical dynamics, much less work has been conducted at the scale of a river basin. Most previous studies on nutrient dynamics at the river basin scale have only attempted to quantify inputs vs. outputs<sup>20</sup> with little

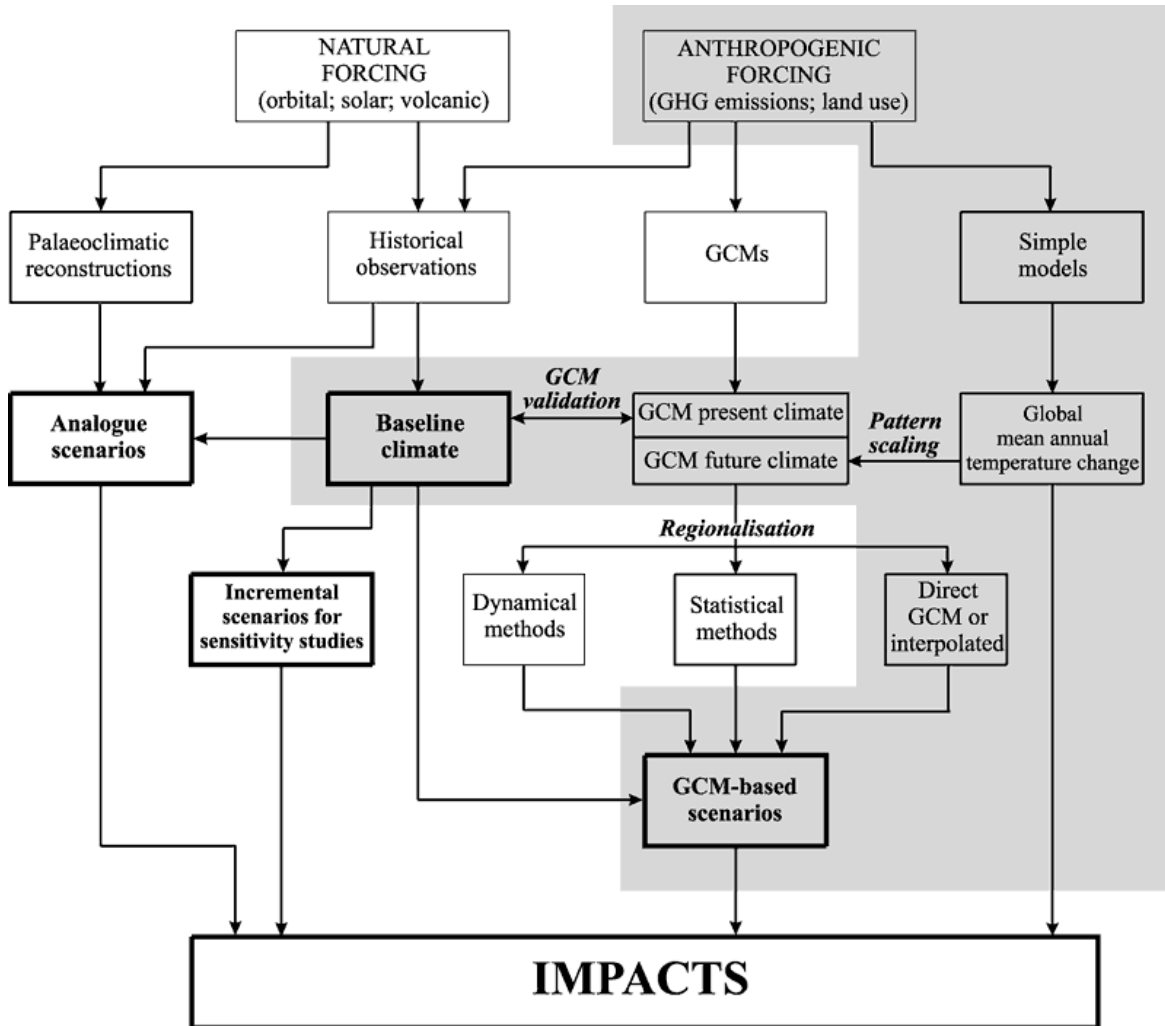


Figure 4. Data sources and procedures for constructing climate scenarios for use in impact assessment

attention paid to local hydrology, let alone to the temporal and spatial variations in those hydrologic processes. Recent research has shown that riverine loading and transport of N (nitrogen), particularly in anthropogenically affected areas (such as the Ohio River), are closely related to hydrological

<sup>18</sup> Gilliom et al., 1995. USGS Circular 1112, 33 p. "Design of the National Water-Quality Assessment Program"

<sup>19</sup> The Long Term Ecological Research Network: [www.lternet.edu](http://www.lternet.edu)

<sup>20</sup> Hydrological Sciences Journal 52:166-180. "Long-term freshwater inflow and sediment discharge into Lake Pontchartrain in Louisiana, USA"

variations between wet and dry cycles<sup>21,15</sup>. In addition, the solubility of inorganic N compounds and the role of N as a limiting nutrient in both aquatic and terrestrial ecosystems<sup>22</sup> makes the dynamics of N closely tied to the hydrologic cycle. As such, linkages among land-use, nutrient dynamics and water balance are clearly needed at larger scales, if a predictive understanding of future water quality and water availability, as well as ecosystem sustainability, is to be developed. Such needs are even more pressing if we consider the dramatic changes in hydrology that are to be expected from weather extremes resulting from global warming.

### ***Relation of proposed work to previous and ongoing work by the investigators***

My previous work on aquatic environments indicates that nutrient dynamics is strongly controlled by spatial and temporal variations in abiotic conditions<sup>23</sup>. Some of my more recent work on estuarine environments has also shown that local hydrology is not only important in controlling nutrient fluxes, but also in determining ecosystem productivity and sediment transport<sup>24</sup>.

In regards to river systems, my collaborators (Drs. Anne Carey and Berry Lyons) have shown that temporal and spatial patterns of hydrologic variation strongly interact with biological uptake and ecosystem cycling to establish the partitioning between retention and transport<sup>15</sup>. They have also shown that this partition is not constant, neither on temporal nor spatial scales. Their studies on the Mobile-Alabama River System<sup>25</sup> and on the Mississippi River<sup>15</sup> have shown that the amount of fixed N placed onto the landscape is not balanced by known export (losses) of N, i.e., a sizeable fraction of the N added to the system is unaccounted for by known losses. Furthermore, as shown for smaller, mixed use watershed, there has been an indication of N gain over time<sup>26</sup>. Dr. Carey and colleagues have suggested that this long-term gain occurs through N storage in soils or in groundwater<sup>15</sup>. From these and some other works there are plenty of indications that hydrology is an important controlling factor determining N loss or storage and that these vary considerably both in temporal and spatial scales.

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<sup>21</sup> J. Am. Water Resour. Assoc. 37:1417-1419. "Nutrient load characterization for the lower Mississippi River"

<sup>22</sup> Biogeochemistry 13:87-115. "Nitrogen limitation on land and in the sea: How can it occur?"

<sup>23</sup> J. Marine Syst. 60:63-74. "Seasonal and spatial controls on the delivery of excess nutrients to nearshore and offshore coral reefs of Brazil"

<sup>24</sup> Env. Chemistry (in review). "Nutrient and biomass exchange between the Antigonish Harbour and St. Georges Bay, Atlantic Canada"

<sup>25</sup> Geochem. Explor. Environ. Anal. 3:239-244. "Nitrogen budget of the Mobile-Alabama River System watershed"

<sup>26</sup> Groundwater 23:68-80. "Effect of agricultural land use on groundwater quality in a small Pennsylvania watershed"

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