# A Coupled Hydrologic-Economic Modeling Framework for Evaluating Alternative Options for Reducing Watershed Impacts in Response to Future Development Patterns

Maria T. Amaya

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John C. Little, Committee Chair

Faye Duchin

Erich T. Hester

Theodore C. Lim

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ABSTRACT

Economic input-output (I-O) and watershed models provide useful results but when seeking to integrate these systems, the structural, spatial, and temporal differences between these models must be carefully considered. To reconcile these differences, a hydrologic-economic modeling framework is designed to couple an economic model with a watershed model. A physically constrained, I-O model, RCOT, is used to represent the economic system in this framework because it provides sectoral detail for a regional economy and calculates physical resource quantities used by these sectors. Uniquely, it also allows for technology options for all sectors and minimizes the resource use based on environmental constraints imposed by the watershed, which adds complexity to the representation of the economic system and its interactions with the watershed system. To represent the watershed system in this framework, the Hydrological Simulation Program-Fortran (HSPF) is used. An HSPF model has been calibrated to represent the hydrological processes of Cedar Run Watershed by the Occoquan Watershed Monitoring Laboratory (OWML). Thus, the capabilities of this framework are demonstrated using strategic scenarios developed to examine future development patterns that may occur within Fauquier County, northern Virginia, and its local basin, Cedar Run Watershed. The scenarios evaluate both the downstream and seasonal impacts on water flow and nitrogen concentration within the watershed, and the changes made within the economic system in response to these impacts. For these scenarios, the most efficient solution is the one that minimizes the use of resource inputs within the economic sectors, including developed land, water withdrawn, and applied nitrogen, which in turn inform watershed health. The scenario results demonstrate that this coupled hydrologic-economic modeling framework can overcome the spatial differences of the individual models and can capture the interactions between watershed and economic systems at a temporal resolution that expands the types of questions one can address beyond those that can be analyzed using these models separately.

# A Coupled Hydrologic-Economic Modeling Framework for Evaluating Alternative Options for Reducing Watershed Impacts in Response to Future Development Patterns

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## GENERAL AUDIENCE ABSTRACT

Water is an essential commodity for human survival, a necessary resource for many industries, and a crucial indicator of environmental health. Rising human populations have created stress on the natural supply of water resources while corresponding economic activities have contributed to the deterioration in water quality. Therefore, it is essential to identify pathways for addressing water use and contamination while also supporting economic progress to achieve sustainable development.

The region of study is Fauquier County, located in northern Virginia, USA. This county has a long association with agricultural production, but it has been experiencing development pressure due to its proximity to Washington DC (50 km southwest). Within Fauquier County lies Cedar Run Watershed (498 $km^2$), a sub-basin of Occoquan Watershed (1,515 $km^2$). Occoquan Watershed drains into the Occoquan Reservoir, which is a drinking water source for close to two million residents in northern Virginia.

The motivation of this research is to design a coupled modeling framework that allows insight to be gained into the interactions that occur between watershed and economic systems. This framework is then used to evaluate how changes in economic activities will cause changes in water use and contamination levels within Cedar Run Watershed and vice versa. By designing strategic scenarios to provide implications about future development patterns that may occur in the region, changes can be anticipated, and conclusions can be reached.

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## Abbreviations and Acronyms

| | |
|---|---|
| $ | dollar |
| $M | million dollars |
| % | percent |
| ac | acre |
| alt | alternative technology |
| BEA | Bureau of Economic Analysis |
| BLS | Bureau of Labor Statistics |
| cfs | cubic feet per second |
| CGE | computable general equilibrium |
| DC | District of Columbia |
| EEIO | environmentally extended input-output |
| ET | evapotranspiration |
| EWR | environmental water requirements |
| ext | external water |
| $ft^3$ | cubic feet |
| gal | gallons |
| GIS | geographic information system |
| GW | groundwater |
| ha | hectare |
| HFR | high-flow requirement |
| HSPF | Hydrological Simulation Program-Fortran |
| IMPLAN | Impact Analysis for Planning |
| I-O | input-output |
| kg | kilogram |
| km | kilometer |
| $km^2$ | square kilometer |
| lb | pounds |
| LFR | low-flow requirement |
| $m^3$ | cubic meter |

| | |
|---|---|
| MAOP | Multicultural Academic Opportunities Program |
| MAR | mean annual runoff |
| MG | million gallons |
| mg/L | milligrams per liter |
| MRIO | multiregional input-output |
| NAICS | North American Industry Classification System |
| NASS | National Agricultural Statistics Service |
| $NH_3$ | ammonia |
| NHGS | New Horizons Graduate Scholars |
| $NO_3^-$ | nitrate |
| OWML | Occoquan Watershed Monitoring Laboratory |
| $Q_{90}$ | monthly flow rate exceeded 90 percent of the year |
| RCOT | Rectangular Choice-of-Technology |
| S1 | scenario 1 |
| S2 | scenario 2 |
| S3 | scenario 3 |
| S4 | scenario 4 |
| S5 | scenario 5 |
| S6 | scenario 6 |
| S7 | scenario 7 |
| S8 | scenario 8 |
| std | standard technology |
| SW | surface water |
| TN | total nitrogen |
| USA | United States of America |
| USGS | United States Geological Survey |
| VGIN | Virginia Geographic Information Network |
| WTM | World Trade Model |
| yr | year |

# Chapter 1 Introduction

## 1.1 Motivations of Research

### 1.1.1 A coupled hydrologic-economic modeling framework

Throughout the 19th and 20th centuries, economic concepts have been applied in water engineering to gain insight into assessing water management concerns across different spatial scales, such as forecasting water demand, negotiating water policy, and evaluating engineering designs (Lund, Cai, & Characklis, 2006). Water serves as a resource used in both production and consumption, as well as a sink for the pollution byproducts of this economic activity. Thus, while water is utilized within economic systems, the impact of economic use on water quantity and quality must be simultaneously considered (Brouwer & Hofkes, 2008).

Beginning in the 1960s and 1970s, hydro-economic modeling has been developed by hydrologists and engineers to represent the hydrologic and economic aspects of a region within a modeling framework (Harou et al., 2009). However, when trying to integrate these hydrologic and economic systems, several challenges have arisen. First, when establishing relationships between variables, economic models often use statistical inference while watershed models are typically based on empirical relationships (Brouwer & Hofkes, 2008; McKitrick, 1998). Second, watershed models are usually spatially defined at the basin scale and economic models are defined by administrative boundaries. Third, watershed models are defined at fine temporal scales, such as hours or days, while economic models are temporally defined at the annual scale (Brouwer & Hofkes, 2008).

Considering the challenges associated with modeling the interactions between economic and watershed systems, a coupled hydrologic-economic modeling framework is designed to meet the following criteria: represent the entirety of a regional economy and a local watershed at an adequate level of sectoral and spatial detail, provide realism by capturing human decisions made within the economic sectors based on environmental constraints imposed by the watershed, model the exchange of information between the two systems in terms of material flows, rather than purely monetary values. Thus, a modular framework is designed that is substantially grounded in the physical reality of a region.

### 1.1.2 Future development patterns

To demonstrate the capabilities of the coupled modeling framework, this research investigates a regional economy, its impacts on a local watershed, and the human decisions made within the economic system in response to those impacts. As the region of study, Fauquier County has a long history of agricultural production, but it has also been experiencing development pressure due to its proximity to the Washington DC metropolitan area. County officials are interested in supporting the agricultural sector of the economy, while avoiding sprawling residential development, by zoning 90% of the county for agricultural development (Rephann, 2015; Fauquier County Board of Supervisors, 2019).

Located within Fauquier County is Cedar Run Watershed (498 $km^2$), a sub-basin of Occoquan Watershed (1,515 $km^2$), which is located 50 km southwest of Washington DC. Occoquan Watershed drains into the Occoquan Reservoir, which serves as a source of drinking water for around two million residents in northern Virginia. Since algal blooms used to be frequent in this watershed, nutrient enrichment and eutrophication are considered primary water quality concerns for the region. Population growth and rapid urbanization are also concerns for Occoquan Watershed (Xu, Godrej, & Grizzard, 2007).

The future will be different in terms of the size, distribution, and behavior of the population, and what policies are needed to encourage certain behaviors and discourage or regulate others. Thus, considering the priorities for this regional economy and the local basin, strategic scenarios are developed to evaluate how alternative future development prospects in Fauquier County, such as agricultural intensification or suburbanization, affect the nitrogen concentration within Cedar Run Watershed. These scenarios also examine how changes in human decisions within different economic sectors, made in response to the physical constraints imposed by the watershed, can alleviate these impacts on water quantity and quality.

## 1.2 Research Objectives

The primary objective of this research is to demonstrate the capabilities of this coupled modeling framework, which is intended to be generalizable so it can be used to represent various locations with different environmental issues, but it will be implemented in

Fauquier County in these initial studies. Thus, the secondary objective of this research is to design illustrative scenarios that examine the implications of alternative development patterns that may occur in Cedar Run Watershed, customize different models integrated in a framework, compile necessary data, and gain insight relevant to Fauquier County. These scenarios are dramatizations based on assumptions about future human activities within Cedar Run Watershed and developed using attributes of the economic database assembled for the county.

### 1.2.1 Interactions between watershed and economic systems

In the first of the three research studies described in this document, a modular hydrologic-economic modeling framework is described. This framework is designed to capture the interactions between an economic system and the watershed that lies within it. A deterministic, physically based model, Hydrological Simulation Program-Fortran (HSPF), is used to represent the watershed system. The Rectangular Choice-of-Technology (RCOT) model, a physically constrained, input-output (I-O) model, is used to represent the economic system as distinct, interdependent, industrial sectors. RCOT also has the unique capability to select among choices introduced within different economic sectors to maximize efficiency, which is achieved by constraining factor use to not exceed the available endowment or a policy constraint (Duchin & Levine, 2011). Thus, this framework captures how changes in economic activity will alter the physical conditions within the local watershed and how changes within the watershed in turn influence decisions made within the economic system. An illustrative example is presented that applies this framework in Fauquier County and Cedar Run Watershed, located in northern Virginia, USA.

The objective of this first study is to answer the following questions: a) How will an increase in economic demand, caused by an increase in agricultural production for export, impact jobs in Fauquier County? b) How will this increase in demand affect the use of resources, specifically land and water, and influence nitrogen loading in Cedar Run Watershed? c) To what extent does the spatial distribution of economic activities and choice of management technology alleviate the severity of this nitrogen loading?

### 1.2.2 Spatial detail of watershed-economic interactions

In the second research study, alternative future development prospects that may occur within Fauquier County are examined along with their impacts on downstream water quality within Cedar Run Watershed at an average annual time scale. The influence of these impacts on human decisions made within different sectors of the local economy are also examined. To conduct this analysis, the modular hydrologic-economic modeling framework is utilized to demonstrate that it can capture the economic-watershed interactions at a finer spatial resolution than either administrative boundaries or watershed criteria, which expands the types of questions that may be addressed be either of the models coupled in this framework.

The objective of this second study is to address the following research questions: a) Can technological innovation in residential water use alleviate the downstream impacts on water quantity and nitrogen concentration caused by upstream residential build-up in Cedar Run Watershed? b) Can strategic crop selection alleviate the downstream impacts on water quantity and nitrogen concentration caused by upstream agricultural intensification in Cedar Run Watershed? c) Does coupling a distributed watershed model with a physically constrained, I-O model provide two-way feedback that captures the interactions between the watershed and economic systems at a level of spatial detail that expands the types of questions that may be addressed by either of the models coupled in this framework?

### 1.2.3 Temporal resolution of watershed-economic interactions

In the third study, several illustrative scenarios involving agricultural expansion and irrigation within Fauquier County are evaluated along with the seasonal increases in nitrogen concentration that occur within Cedar Run Watershed because of the new agricultural activity. The influence of these seasonal impacts on selections made among different conjunctive use strategies available within the crop farming sector of the economy are also examined. The modular hydrologic-economic modeling framework is utilized in this analysis to demonstrate that it can capture the interactions between economic and watershed systems at sub-annual temporal scales, which expands the range of questions that can be addressed using the models linked in this framework.

The objective of this third study is to answer the following research questions: a) Can the implementation of conjunctive use alleviate the seasonal impacts on water quantity and nitrogen concentration caused by agricultural intensification and irrigation within Cedar Run Watershed? b) Does a 3-month timestep produce different output results from this coupled hydrologic-economic modeling framework than when a 6-month timestep is used? c) Does coupling a physically constrained, I-O model with a continuous watershed model provide two-way feedback that captures the interactions between the economic and watershed systems at a temporal resolution that expands the types of questions that may be addressed by either of the models coupled in this framework?

### 1.3 Document Organization

The remaining chapters of this document are organized as follows:

**Chapter 2** is a research paper describing the coupled hydrologic-economic modeling framework and its first implementation in Cedar Run Watershed, which lies with Fauquier County in northern Virginia, USA. This research paper was originally published in *Frontiers in Water*, volume 3, on June 3, 2021. The author retains the copyright to this manuscript.

**Chapter 3** is a research paper that analyzes alternative future development prospects that may occur in Fauquier County and their downstream impacts in Cedar Run Watershed using the modular framework described in Chapter 2. Special focus is placed on the spatial detail of the economic and watershed interactions in the study area. This research paper has been submitted to *Sustainability*.

**Chapter 4** is a research paper that examines agricultural intensification, which may occur in the future within Fauquier County, and its seasonal impacts on Cedar Run Watershed using the modular framework described in Chapter 2. Special focus is placed on the temporal resolution of the economic and watershed interactions in the study area. This research paper has been submitted to *Frontiers in Water*.

**Chapter 5** presents a final summary of the research studies described in this document, an outline of the conclusions from each study, and recommendations for future research.

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# Chapter 2 A coupled hydrologic-economic modeling framework for scenario analysis

Maria Amaya[1], Ayden Baran[2], Carlos Lopez-Morales[3], John C. Little[1]

[1]Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, Virginia, USA

[2]Occoquan Watershed Monitoring Laboratory, Virginia Tech, Manassas, Virginia, USA

[3]Centro de Estudios Demográficos, Urbanos y Ambientales, El Colegio de México, Ciudad de México, México

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## 2.1 Abstract

To capture the interactions between hydrologic and economic systems necessary for modeling water quality at a sufficient level of detail, we have designed a modular framework that couples an economic model with a watershed model. To represent the economic system, the Rectangular Choice-of-Technology (RCOT) model is used because it represents both the physical and monetary aspects of economic activities and, unlike traditional input-output or general equilibrium models, it can optimize choices among operational technologies in addition to the amount and location of production. For the first implementation of this modeling framework, RCOT is coupled with a watershed model, Hydrological Simulation Program-Fortran (HSPF), which is calibrated to represent Cedar Run Watershed in northern Virginia. This framework is used to analyze eight scenarios related to the expansion of agricultural activity in Fauquier County. The database for RCOT uses county-level input-output data, representative of this region in 2012. Thus, when crop farming is expanded to fully utilize the farmland available in the watershed, the nitrogen concentration at the outflow of the watershed increases from 0.6 to 4.3 mg/L. However, when RCOT could select between a standard and a more nitrogen-efficient management practice, the outflow nitrogen concentration only increases to 2.2 mg/L because RCOT selects the more resource-efficient practice. Building on this modular framework, future work will involve designing more realistic scenarios that can evaluate policy options and regional planning decisions in a wide range of watersheds.

**Keywords:** modeling, framework, economic, hydrologic, watershed.

## 2.2 Introduction

The engineering and economic disciplines have historically maintained an association since economic costs and benefits are important concerns when designing, building, and maintaining infrastructure. However, the role of economic principles has begun to expand in engineering, particularly in the field of water resources engineering where concerns of water availability and quality have become more deeply intertwined with socio-economic impacts. Applying economic concepts in water engineering can enhance insight into forecasting water demand, evaluating engineering designs, negotiating water policy, as well as understanding water management concerns across local, regional, and global scales (Lund, Cai, & Characklis, 2006). Water is a resource used both in production activities and directly by consumers, but it also serves as a sink for the pollution byproducts of production and consumption. Therefore, while water must be utilized for economic purposes, the impact of economic use on water quantity and quality must be simultaneously considered (Brouwer & Hofkes, 2008).

Hydro-economic modeling has been developed by hydrologists and engineers to represent the interactions between hydrologic and economic systems. The integration process may include considering multiple disciplinary views to a problem, linking different system or process models, harmonizing different scales of process operation, assessing the effects of management options on various economic, and environmental issues, or any combination of these concepts (Kelly et al., 2013). Typically, hydro-economic models combine water quantity models, water allocation models, or water quality models with economic variables of supply and demand on the basis that water carries economic value. However, several challenges can occur when trying to combine water and economic systems. First, hydrologic models usually are spatially defined by watershed criteria while economic models are typically defined by administrative boundaries. Additionally, hydrologic models can be temporally defined from hours to months while typical economic models are temporally defined in years or longer. Furthermore, hydrologic models are typically based on theories or empirical relationships among variables while economic models often use statistical inference to establish relationships among variables (Brouwer & Hofkes, 2008; McKitrick, 1998). These challenges can be addressed differently depending on the modeling approach being utilized and the application of the modeling framework. Three approaches used for hydro-economic modeling include the holistic, computable general equilibrium (CGE), and modular approaches (Brouwer & Hofkes, 2008). Each approach is examined in more detail in the following sub-sections.

### 2.2.1 Holistic Approach

The holistic modeling approach incorporates the hydrologic and economic components of a region into a single integrated software package. As a result, all information is transferred internally within the model and data transformation is not a primary concern. On the other hand, both the hydrologic and economic components must be represented by a single solver, and thus each component must be effectively simplified to minimize complexities within that solver (Brouwer & Hofkes, 2008; Cai, McKinney, & Lasdon, 2003). The holistic modeling approach has been applied in multiple case studies, including one in the Maipo River basin in Chile (Cai, Ringler, &You, 2008) and several located in Spain (Escriva-Bou, Pulido-Velazquez, & Pulido-Velazquez, 2017; Kahil, Ward, Albiac, Eggleston, & Sanz, 2016; Pulido-Velazquez, Andreu, Sahuquillo, & Pulido-Velazquez, 2008). This approach is typically characterized by a model being developed to simulate hydrologic and economic relationships by presenting the basin as a linked network of supply nodes, such as reservoirs and rivers, and demand nodes representing irrigation, municipal, and industrial entities. Each source node has an associated water balance or storage operation while the demand sites account for short-term economic costs and benefits (Cai, Ringler, & You, 2008; Harou et al., 2009). These holistic models can provide insight into concerns of hydrologic stress resulting from economic productivity, but they have historically lacked sectoral detail or comprehensive representation of a whole economy (Brouwer & Hofkes, 2008).

### 2.2.2 CGE Approach

Traditionally, the holistic approach focuses on a comprehensive hydrological system with some extension to economic variables. However, because this approach lacks a detailed economic system, CGE models have been employed in frameworks that integrate hydrologic and economic systems. There have been multiple applications of the CGE approach in integrated hydro-economic analysis, such as in an analysis of China’s whole economy (Jiang, Wu, Liu, & Deng, 2014) as well as in more recent case studies (Kahsay et al., 2019; Knowling et al., 2020). These models are economic models capable of representing price-dependent market interactions and can be extended to assess water policy. While this approach can effectively depict economy-wide impacts, it lacks intricate detail in representing hydrologic processes (Bohringer & Loschel, 2006; Brouwer & Hofkes, 2008). Furthermore, CGE models may be useful at depicting how a whole economy is impacted by changes in watershed conditions, but hydrologic variables must be transformed into monetary values to be incorporated into these models (Zhang, 2013).

While CGE models have been promoted as an approach to evaluate the interactions between economic and hydrologic systems, several shortcomings have been identified regarding the utilization of these models for broader sustainability assessment, which are fully detailed in Scrieciu (2007) and summarized here. First, the economic theory employed in these models places great emphasis on the role of market interactions in addressing environmental issues. CGE models also operate using the mainstream theory that behavior is driven by the maximization of personal utility as represented by consumption, which excludes other drivers of human behavior (Zhang, 2013). Additionally, CGE models may be unsuitable for representing changing economies since they have limitations in presenting transitions in technology that can occur because of the implementation of environmental policy. Finally, these models alone are not able to adequately capture the localized impacts of large-scale environmental problems. Therefore, an economic model with more sectoral and spatial disaggregation may be better suited for assessing the economic system and its interactions with an environmental system. Furthermore, a model capable of representing the economic components with adequate complexity, coupled with other independently constructed models, could provide a more comprehensive assessment than solely relying on a CGE modeling framework where environmental variables must conform to the underlying principles of CGE models (Scrieciu, 2007).

### 2.2.3 Modular Approach

When applying the modular approach, hydrologic and economic models are loosely connected and output data from one model is used as input data for the other (Brouwer & Hofkes, 2008). The modular approach allows for the use of established models and thus enables innovation in new conceptual integration rather than building a simplified model as is the case when applying the holistic modeling approach. However, the data must be correctly transformed for information to be transferred between each model (Cai et al., 2003; Harou et al., 2009), but it has been successfully implemented in several past studies (e.g., Esteve, Varela-Ortega, Blanco-Gutierrez, & Downing, 2015). Since the modular approach allows for the use of independent models, input-output (I-O) economic models, which are part of an alternative modeling tradition to CGE models, may be used to represent the economic system within the modeling framework. These models provide sectoral detail of a regional economy and can capture the inter-sectoral flow of goods among these economic sectors. Furthermore, I-O models can calculate factor quantities, including natural resources, used by each sector and can represent economic demand in physical or monetary units. On the other hand, these models do not typically capture the spatial distribution of these quantities (Harou et al., 2009). However, Jonkman, Bockarjova, Kok, and Bernardini (2008), designed a modular framework to analyze the Netherlands' entire economy and a geographic information system (GIS) was used to spatially transform data so that it could be transferred between a hydrologic model and an I-O model. Thus, spatial disaggregation is feasible with I-O models.

### 2.2.4 Utilizing constrained optimization, I-O models

In general, I-O models are sufficient to use in the modular approach to hydro-economic modeling, but specifically, constrained optimization, I-O models are the most suitable alternative to CGE models in representing an economic system within a hydrologic-economic framework. The World Trade Model (WTM) and Rectangular Choice-of-Technology (RCOT) models are recent extensions to this family of models. WTM was developed as a linear programming model that selects among choices of geographic locations (Duchin, 2005). Similarly, RCOT is an input-output, linear programming model that, unlike the traditional input-output model or CGE models, endogenously considers choices among operational technologies based on constraints to minimize use of factors of production, which effectively represents human behavior in response to changing environmental conditions (Duchin & Levine, 2011). Since WTM and RCOT are based on the same economic logic, the two models can be easily integrated so that the choices of alternative technologies and of the spatial location of production may be considered

(Duchin & Levine, 2011, 2012). The WTM and RCOT models can represent both the physical and monetary aspects of economic activities. These models can clearly represent the physical availability of water as well as its corresponding costs and price.

The WTM/RCOT model was used in a case study to evaluate water withdrawal policies and their economic implications for the different regions of Mexico (Lopez-Morales & Duchin, 2015). More recently, RCOT has been used to represent the generation, treatment, and discharge of wastewater within the regional economy of Mexico City. In this case study, the choice of technology mechanism within RCOT was used to select between alternative wastewater infrastructure that may be utilized to alleviate overexploitation of natural water sources (Lopez-Morales & Rodriguez-Tapia, 2019). There is a direct interdependence between availability of water and its subsequent quantity and cost for economic activities. As a result, the choice selection among specific technologies available to different economic sectors can change and ultimately affect prices of goods. This model represents the quantity of inputs required by an economic sector to produce a unit of its output using the technologies in place, making it a structural model based on causal relationships rather than a model based on statistical inference. Therefore, RCOT has the necessary complexity to represent the economic system, and the use of natural resources within that system, as well as the compatibility to be coupled with an independent hydrologic model in a modular framework.

### 2.2.5 Research Objectives

In this paper, we describe a modular framework designed to capture the interactions between a watershed and an economic system that lies within it. RCOT is used to represent the economic system while an HSPF model is used to represent the watershed system. The novelty of this framework lies both in the utilization of RCOT and in the relationship between the two models. RCOT is a regional-scale model and can represent an entire economy with adequate sectoral detail, which typically is lacking in the holistic modeling approach. Additionally, its ability to select among choices in production locations and technologies provides realism in terms of representing human decisions amidst changing economies as well as providing some spatial detail, which has historically been missing from economy-wide models. Furthermore, because RCOT can represent the economy in terms of physical phenomena, this framework can capture how changes in economic activity will alter the physical conditions within the local watershed and how these changes within the watershed in turn limit the economic activity that can occur. The result is a framework that is more substantially grounded in the physical reality of the study location.

Next, we present an illustrative example where this framework is applied in Fauquier County and Cedar Run Watershed, which are in northern Virginia, United States. A rural location not looking to take dramatic new initiatives is intentionally chosen so that this research can begin with simple, illustrative scenarios before moving on to more complex socio-economic settings and the subject of active regional planning. Fauquier County seeks to avoid extensive urban development, but current policy still allows for the intensification of agricultural development. However, such development would have negative impacts on the local watershed, which is in a region that has experienced water quality issues over the last few decades. Thus, the following questions are addressed:

1. How will an increase in economic demand, caused by an increase in agricultural activity, impact jobs in the county?
2. How will an increase in demand affect the use of resources, specifically land and water, and influence nitrogen loading in the local watershed?
3. To what extent does the spatial distribution of economic activities and choice of management practice alleviate the severity of the nitrogen loading?

## 2.3 Study Location

### 2.3.1 Cedar Run Watershed: Sub-basin of Occoquan Watershed

The region of study is located within a sub-basin of the Occoquan Watershed, which is a 1,515 $km^2$ watershed located 50 km southwest of Washington DC. The watershed drains into the Occoquan Reservoir, which is one of two major drinking water sources in the watershed (the other is Lake Manassas). The Occoquan Reservoir serves about two million residents in northern Virginia while Lake Manassas is the primary drinking water source for the City of Manassas. The watershed contains sections of four counties and the land is characterized by agriculture, forest, and urban areas. Nutrient enrichment, specifically nitrogen and phosphorus, and the associated eutrophication have been primary water quality issues as algal blooms used to be quite frequent. Furthermore, rise in population and rapid urbanization are also concerns for the Occoquan Watershed. As a result, Occoquan Watershed Monitoring Laboratory has been conducting research into the surface water quality of the watershed under varying climate and land-use conditions for the past several decades. They divided the watershed into seven sub-basins and have already calibrated an HSPF model on many occasions using local data to represent each sub-basin. The primary objective of this linked modeling system is to simulate the interactions of the water supply system so that plant managers can optimize operation in response to potential future conditions (Xu, Godrej & Grizzard, 2007).

Each HSPF model is set up to output results for watershed outflow, nitrate, phosphorus, and sediment loading. However, rather than working with multiple watershed models during this preliminary study, it is more practical to utilize a single HSPF model, and therefore a single sub-basin of the Occoquan Watershed, when developing the initial coupled hydrologic-economic modeling framework. Out of the seven sub-basins, Cedar Run Watershed (498 $km^2$) is selected for several reasons. First, it is one of the largest sub-basins of Occoquan Watershed and it is also not dependent on data supplied by a connecting HSPF model. Additionally, the HSPF model representing Cedar Run Watershed divides the watershed into fifteen segments and twelve of the fifteen segments lie within Fauquier County (Figure 2-1). Finally, much of the watershed presently contains agricultural land use with minimal urban development, as described in the next section.

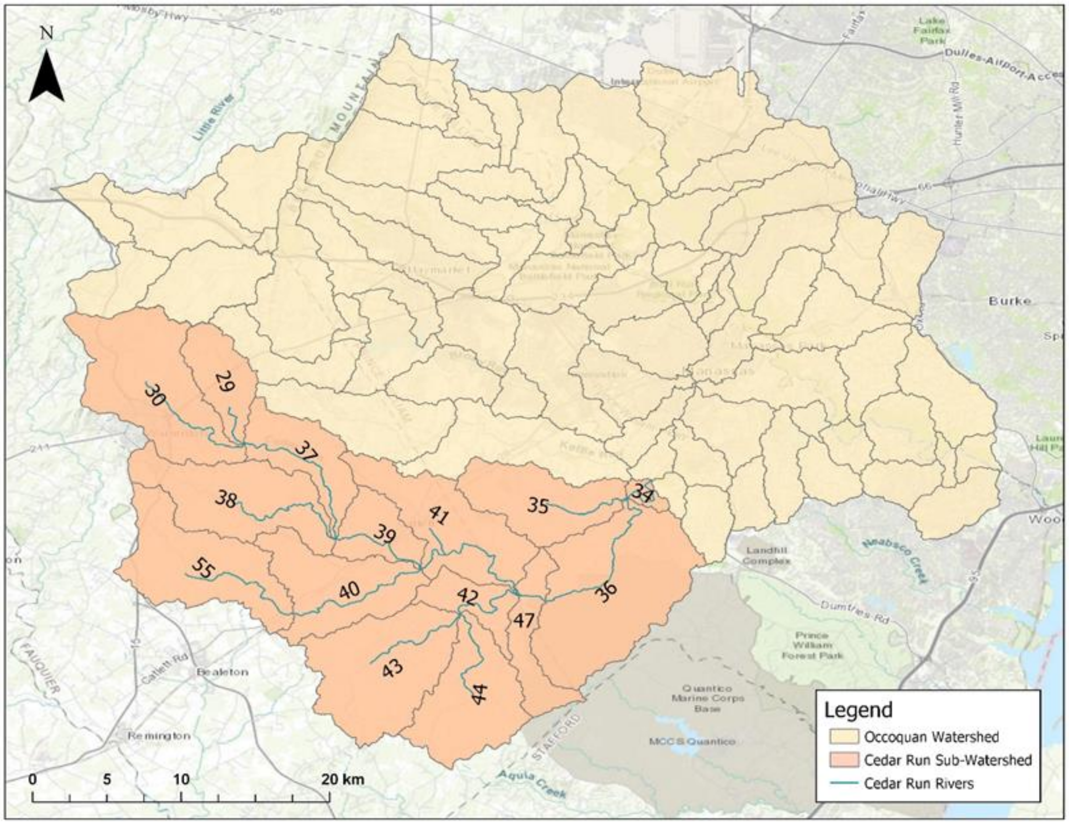


**Figure 2-1.** Occoquan Watershed divided into segments with numbered segments representing Cedar Run Sub-watershed

### 2.3.2 Fauquier County

Fauquier County has a long tradition of agricultural land use. During the 20th century, dairy and beef cattle industry was very prominent within the county. However, this industry has declined within the past several decades. In 1997, 50% of the farms in Fauquier County were devoted to the cattle industry and, by 2012, only 35% of the farms were devoted to this industry. Meanwhile, county grain production has remained stable or increased between 1990 and 2012. Traditional farming has also declined as the number of full-time farmers has decreased by 24% between 2002 and 2012 while the number of part-time farmers has increased by 14% during that same period. In the face of growing human development in the urban areas of the county, officials have specified that they would like to maintain the “rural character” of much of the county by preserving its farmland and ensuring that the county maintains the agricultural sector of its economy. The officials also seek to avoid sprawling urban development and sustain compact settlement patterns. As depicted in Figure 2-2, these concerns have been addressed through the implementation of zoning districts to restrict land use with about 90% of the county set aside for agriculture (Rephann, 2015; Fauquier County Board of Supervisors, 2019).

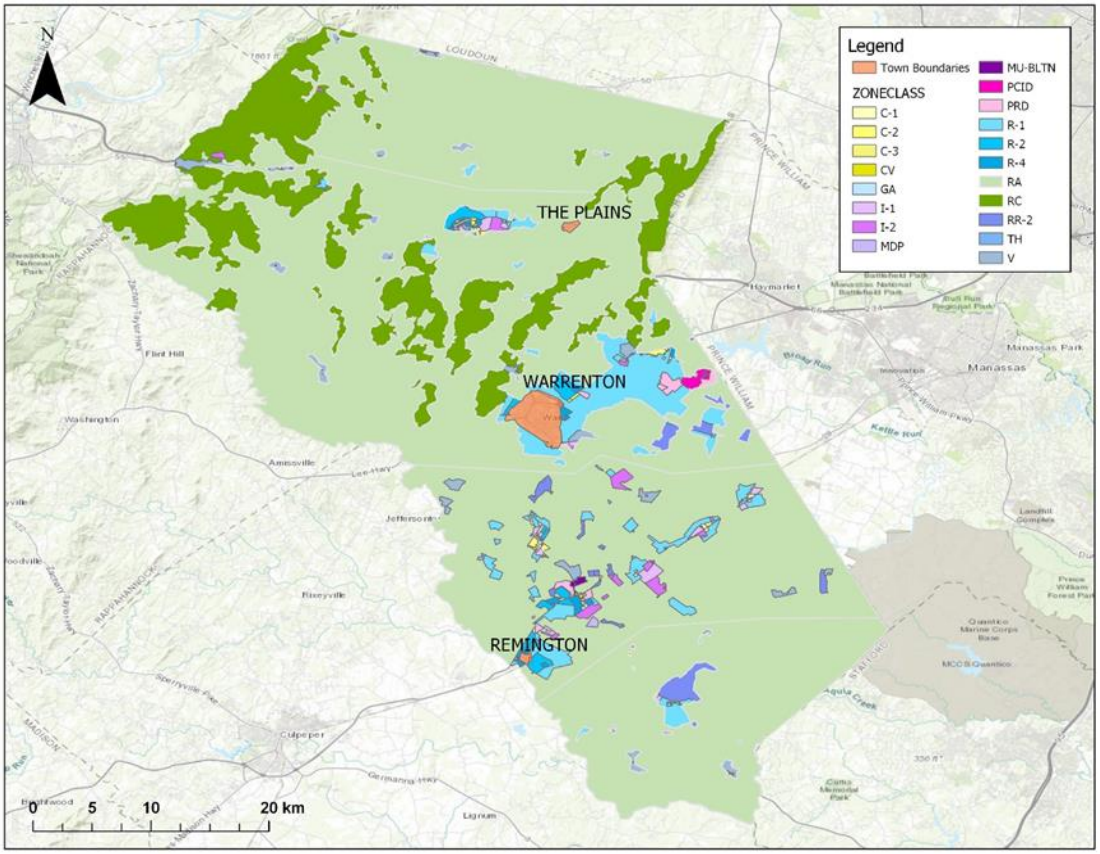


**Figure 2-2.** Fauquier County Development Zones**.** Note: (C1) commercial neighborhood, (C2) commercial highway, (C3) shopping center, (CV) commercial village, (GA) garden apartments, (I1) industrial park, (I2) industrial general, (MDP) manufactured dwelling park, (MU-BLTN) mixed use Bealeton, (PCID) planned commercial industrial development, (PRD) planned residential development, (R1) residential 1 dwelling unit/acre, (R2) residential 2 dwelling unit/acre, (R4) residential 4 dwelling unit/acre, (RA) rural agriculture, (RC) rural conservation, (RR2) rural residential, (TH) townhouses, (V) village

## 2.4 Methodology

### 2.4.1 RCOT Model

The most basic I-O model is composed of two model components: the primal quantity model and a dual price model. The primal model calculates economic output for *n* distinct economic sectors, such as agriculture, manufacturing, and construction, and *k* factors of production in physical or monetary units of output. Factors of production are required inputs that are themselves not produced, including capital and labor as well as water, land, and other natural resources. The following equations are utilized in the primal model:

$$(\mathrm{I} - \mathrm{A})\mathrm{x} = \mathrm{y} \;\rightarrow\; \mathrm{x} = (\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y} \tag{2.1}$$

$$\varphi = \mathrm{Fx} \rightarrow \; \varphi = \; \mathbf{F}(\mathbf{I} - \; \mathbf{A})^{-1}\mathbf{y} \tag{2.2}$$

where,

A = coefficient matrix (n × n), F = factor requirements per unit of output matrix (k × n), y = final demand vector (n × 1), x = economic output vector (n × 1), I = identity matrix (n × n), φ = factor use vector (k × 1)

The dual model calculates unit cost associated with each economic sector using the following equation:

$$\mathbf{p} = (\mathbf{I} - \mathbf{A}')^{-1}\mathbf{F}'\boldsymbol{\pi} \tag{2.3}$$

where,

π = vector of factor prices (k × 1), p = sectoral price vector (n × 1), A' = transpose of matrix A, F' = transpose of matrix F

As an extension of the basic I-O model, RCOT captures interdependencies between consumption and production as well as among sectors dependent on each other's outputs. Uniquely, RCOT also considers choices among operational technologies based on certain factor constraints. There is a direct interdependence between quantity and cost since a change in availability of a resource or in its unit price can change the choice selection among specific technologies available to different economic sectors (Duchin & Levine, 2011).

RCOT is written as a linear program with $n$ sectors, $t$ technologies, and $k$ factors of production. The primal model specifies $t$ technologies for the $n$ sectors where $t \geq n$, which is why the model is referred to as "rectangular." Parameters and variables distinguish not only among sectors, but also alternative technologies, which are denoted by an asterisk. The primal model utilizes the following objective function:

$$\text{Minimize } \boldsymbol{M} = \boldsymbol{\pi}'\mathbf{F}^*\mathbf{x}^* \tag{2.4}$$

$$\text{such that } (\mathbf{I} - \mathbf{A}^*)\mathbf{x}^* \geq \mathbf{y} \text{ and } \mathbf{F}^*\mathbf{x}^* \leq \mathbf{f}$$

where,

$x^*$ = economic output vector $(t \times 1)$, y = final demand vector $(n \times 1)$, $A^*$ = coefficient matrix $(n \times t)$, f = factor endowments vector $(k \times 1)$, $F^*$ = matrix requirements per unit of output $(k \times t)$, π = vector of factor prices $(k \times 1)$

This objective function minimizes factor use while ensuring that production still satisfies final demand ($y$) and that factor use does not exceed factor availability (f).

The dual price model maximizes the value of final demand net of rents on scarce resources using the following objective function:

$$\text{Maximize } \boldsymbol{W} = \mathbf{p}'\mathbf{y} - \mathbf{r}'\mathbf{f} \tag{2.5}$$

$$\text{such that } (\mathbf{I}^* - \mathbf{A}^*)'\mathbf{p} \leq \mathbf{F}^{*\prime}(\boldsymbol{\pi} + \mathbf{r})$$

where,

y = final demand vector $(n \times 1)$, $A^*$ = coefficient matrix $(n \times t)$, $I^*$ = identity matrix $(n \times t)$, f = factor endowments vector $(k \times 1)$, $F^*$ = matrix requirements per unit of output $(k \times t)$, p = sectoral prices vector $(n \times 1)$, r = factor scarcity rents vector $(k \times 1)$

The endogenous variables in Equation 2.5 are prices of goods and services (p) and rents on factors that are fully utilized (r). There would be no feasible solution for a specified scenario if the required resource endowments are insufficient to meet the specified consumer demand (Duchin & Levine, 2011).

### 2.4.2 HSPF Model

As mentioned previously, an HSPF model has already been calibrated using local data to represent the hydrological behavior of the Cedar Run Watershed during the 2012 base year. Calibration was carried out using data collected from 2008 to 2010, while the validation process utilized data from 2011 to 2012. This data includes regional cloud cover, wind speed, air temperature, and dew point temperature, which were all provided by Washington Dulles International Airport weather station as well as precipitation, which was provided by the rain gauge station located within the watershed. Potential evapotranspiration and solar radiation data were also obtained for calibration using established estimation methods (Bartlett, 2013; Xu, 2005). While there are other more mechanistic models than HSPF as well as more statistical types of watershed models, this model is selected primarily for convenience and because of the long history of successful application in this watershed. Furthermore, it is considered adequate for an initial demonstration of the proposed coupled framework.

HSPF is a structural model designed to represent both natural and developed watersheds. It has the capacity to model both surface and subsurface water quantity and quality. Since it operates in a time series, HSPF represents the processes that are occurring within a specified length of time by generating information at a designated time step that can range from minutes to days. To analyze watershed behavior, HSPF divides the watershed into channel reaches and land segments. The user can utilize the SCHEMATIC block to specify the area and types of land present within these segments. Furthermore, HSPF is composed of application modules used to represent characteristics of each type of segment. One application module, referred to as PERLND, represents permeable land segments, while another module represents impermeable land segments, and a third module, RCHRES, is used to represent the channel reaches. Each of these modules contain sub-modules that simulate specific functions within the segments and these sub-modules can be active or inactive depending on user specifications. In addition to application modules, HSPF also has utility modules that link the application modules and manage the generated data and results (Bicknell et al, 2001).

Water quantity processes that are modeled within the PERLND module are primarily controlled by the sub-module PWATER. The purpose of this sub-module is to simulate the water budget for each pervious land segment, which is accomplished using a water budget equation to predict total runoff from a pervious surface. Additionally, the PQUAL sub-module is used to simulate the movement and fate of water quality constituents from pervious surfaces to the outflows, such as nitrate, phosphorus, and sediments produced by land erosion. On impervious surfaces, the water budget is determined by a sub-module that determines how much moisture is retained within the land segment and how much of that moisture becomes runoff or evaporates. Furthermore, another sub-module simulates the hydraulic behavior of the water within each channel reach and functions under the assumption that complete mixing and unidirectional flow occurs within each channel reach. To determine the appropriate function for outflow from the channel, the user must specify the fate of the outflow, such as whether it will flow into another channel or if it will be withdrawn for irrigation or other purposes (Bicknell et al, 2001).

### 2.4.3 Coupled Modular Framework

In the coupled modular framework (Figure 2-3), changes within the watershed are driven by the optimized economic model. Changes in economic activity within a watershed are represented by changing the final demand associated with the specified sectors within the economy. These values are exogenous variables presented in the y vector of RCOT and can reflect real-world changes, such as an expansion of residents or an increase in production of goods and services for export. Furthermore, the exogenous variables presented in the f vector of RCOT, factor endowments, would include not only the workforce available for economic activity, but also the land and water available within the watershed.

Once these variables are input into RCOT, the economic model is run to obtain endogenous variables. These variables include the economic output from each sector, presented in the x vector of the model, and the factor quantities required to achieve final demand, which are presented in the $\varphi$ vector. Price per economic sector would also be output in the p vector produced by the dual price model of RCOT. These vectors are shown in Figure 2-3 as outputs from the economic model.

Several values of output from the $\varphi$ vector of RCOT's primal model can be used to couple the economic model with the watershed model, specifically the land required, water withdrawn, and the fertilizer applied to achieve final demand. The input characteristics of the HSPF watershed model are adjusted to reflect these changes in factor use. Since RCOT presents these output values in physical units, the transfer of information to HSPF is straightforward. Each watershed segment is divided into different land use categories, which are each defined based on land surface permeability. Increases in land requirements from RCOT translate into changes in area associated with these different categories of land and are exogenously defined within the SCHEMATIC block of HSPF. Additionally, increases in water withdrawals translate into exogenous changes in point source water extraction from the watershed within the RCHRES module of HSPF. Increases in nitrogen application translate into exogenous changes in the dry deposition of nutrients, such as nitrate, ammonia, or a combination of the two, within the watershed using the PQUAL sub-module of PERLND.

Once the characteristics of the watershed have been adjusted in response to the changes in economic activity, HSPF is run to determine the fate of the water and applied nutrients, resulting in the endogenous variables of water quantity and nutrient concentrations that flow through each segment of the watershed. These outputs, shown in Figure 2-3, are dependent on parameters, such as precipitation, runoff, and infiltrations rates, that have been previously established during the HSPF calibration process. Finally, the water availability and nutrient allowances presented in the f vector must be adjusted to reflect the physical changes that have occurred within the watershed because of previous economic activity before RCOT may be run for the next timestep. If more water is withdrawn from the watershed to support current economic expansion, then less water will be available for any future economic expansion. As a result, a more water-efficient technology may be implemented in different sectors, even if it is more expensive than the standard practice because one of RCOT's objective functions is to minimize factor use. Thus, this framework captures how changes in economic activity will alter the physical conditions within a watershed and how these physical changes will in turn limit economic activity or influence economic decisions.

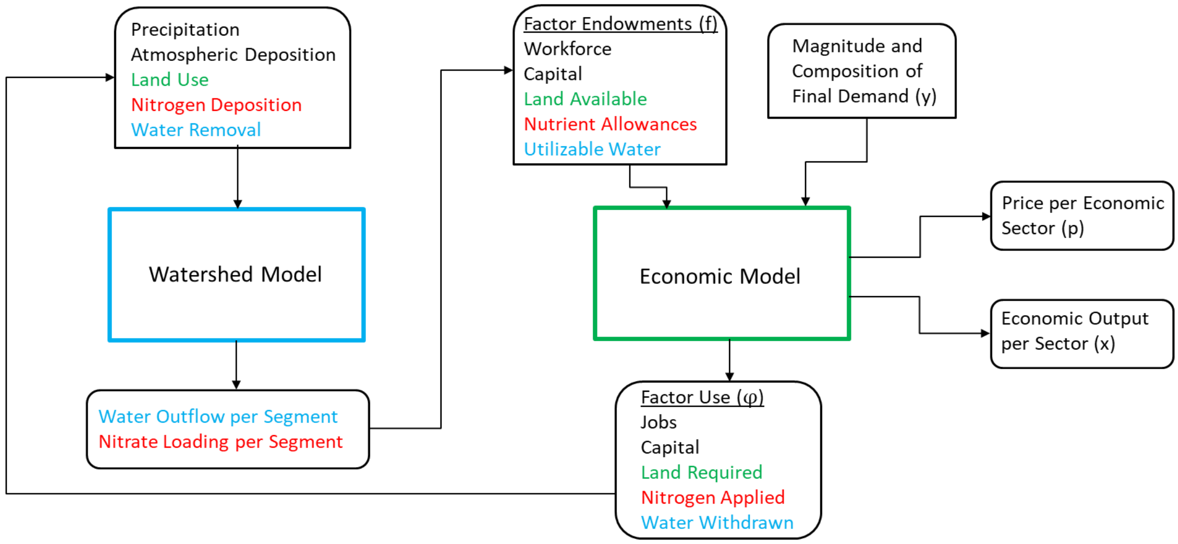


**Figure 2-3.** Conceptual modular framework for coupling a constrained optimization economic model (RCOT) with a watershed model (HSPF). Note: Green- units of land use, Red- units of nitrogen, Blue- units of water, Sharp-edged rectangles- modeling software, Soft/Sharp-edged rectangles- model inputs, Soft-edged rectangles- model outputs

### 2.4.4 Building Baseline Economic Database

This study requires the construction of a county-level database to represent Fauquier County's economy and to distinguish between the sectors of interest for this analysis. Fortunately, monetary county-level, input-output data is available from a private company called IMPLAN Group, LLC. IMPLAN Group compiles their county-level datasets by gathering data from various sources, including the United States Bureau of Economic Analysis (BEA) and Bureau of Labor Statistics (BLS), and providing estimates for unavailable data while benchmarking them against other data to ensure as much accuracy as possible. Economic data is obtained for Fauquier County representative of the year 2012, which serves as the base year. To begin, the county input-output transaction table (Z) and industry final demand data (y) provided by IMPLAN Group are aggregated into seven basic industrial sectors using an aggregation matrix and following the guidelines provided by Miller and Blair (2009). These sectors, including agriculture, mining, construction, manufacturing, utilities, professional services, and government services, are aggregated based on the North American Industry Classification System (NAICS) established by the United States Census Bureau (2017). Once the transaction table is aggregated, the technical coefficient (A) matrix is calculated using the data from the transaction table and economic output data provided by IMPLAN Group, as follows:

$$\mathrm{A} = \begin{bmatrix} z_{11}/x_1 & \cdots & z_{1n}/x_n \\ \vdots & \ddots & \vdots \\ z_{n1}/x_1 & \cdots & z_{nn}/x_n \end{bmatrix} \tag{2.6}$$

Next, the agriculture sector is disaggregated into three specific sectors, crop farming, animal husbandry, and other agricultural activities, for a more detailed analysis. The finalized A matrix is displayed in Table 2-1. Total sector output is calculated for the 2012 base year using this A matrix as well as the aggregated final demand ($y$) vector (Equation 2.1). The resulting output (x) vector is compared to the sector output data provided by IMPLAN Group for 2012 to verify that this model accurately represents the economy of Fauquier County. The results produced by the model are within the same range as the provided data.

**Table 2-1.** Technical coefficient matrix (A) for Fauquier County 2012

| | Crop Farming | Animal Husbandry | Other Agricultural Activities | Mining | Construction | Manufacturing | Trade, Transportation, Utilities | Professional Services | Government Services |
|---|---|---|---|---|---|---|---|---|---|
| **Crop Farming** | 0.0376 | 0.0001 | 0.0170 | 0.0001 | 0.0002 | 0.0038 | 0.0000 | 0.0000 | 0.0000 |
| **Animal Husbandry** | 0.0683 | 0.1058 | 0.0246 | 0.0001 | 0.0003 | 0.0055 | 0.0000 | 0.0000 | 0.0000 |
| **Other Agricultural Activities** | 0.0115 | 0.0115 | 0.0758 | 0.0001 | 0.0003 | 0.0054 | 0.0000 | 0.0000 | 0.0000 |
| **Mining** | 0.0009 | 0.0009 | 0.0009 | 0.0153 | 0.0058 | 0.0004 | 0.0030 | 0.0003 | 0.0006 |
| **Construction** | 0.0047 | 0.0047 | 0.0047 | 0.0516 | 0.0003 | 0.0031 | 0.0043 | 0.0170 | 0.0111 |
| **Manufacturing** | 0.0005 | 0.0005 | 0.0005 | 0.0001 | 0.0088 | 0.0019 | 0.0020 | 0.0012 | 0.0001 |
| **Trade, Transportation, Utilities** | 0.0432 | 0.0432 | 0.0432 | 0.0341 | 0.0789 | 0.0466 | 0.0418 | 0.0175 | 0.0016 |
| **Professional Services** | 0.0446 | 0.0446 | 0.0446 | 0.1088 | 0.0562 | 0.0622 | 0.1350 | 0.1723 | 0.0109 |
| **Government Services** | 0.0017 | 0.0017 | 0.0017 | 0.0008 | 0.0003 | 0.0017 | 0.0084 | 0.0021 | 0.0003 |

To build the factor requirement per unit of output (F*) matrix, six factors of production are identified as requirements for each sector, specifically land, labor, capital, water withdrawn, nitrogen applied as fertilizer and nitrogen applied as manure. Annual labor and capital requirements are calculated using IMPLAN sectoral data for labor, capital, and economic output. Water withdrawn per unit of output for each sector is determined using county water data available from the United States Geological Survey (USGS, 2010) as well as data obtained from an input-output database assembled by the Green Design Institute at Carnegie Mellon University (Blackhurst, Hendrickson & Vidal, 2010). Additionally, fertilizer requirements are assumed based on county data available from the National Agricultural Statistics Service (NASS). Furthermore, land requirements per sector are assumed based on county zoning data provided by the Fauquier County GIS Office (2014). However, these land requirements had to be adjusted since the zoning data did not consider land that had not yet been developed or cleared for a specific use. Therefore, land cover data obtained from the Virginia Geographic Information Network (VGIN, 2016) is used in combination with the zoning data to determine how much land in each zone is cleared or wooded, which is assumed to be an indicator of developed and undeveloped land, respectively.

### 2.5 Illustrative Application

The economic database is established using Fauquier County data from 2012 and an HSPF model has already been calibrated and validated to represent Cedar Run Watershed using local data collected between 2008 and 2012. This data is then used to analyze a set of illustrative scenarios intended to demonstrate the power of the modeling approach and the capabilities of the coupled framework. These scenarios are performed at the annual time scale. All inputs and outputs for the economic model are representative of one year of economic activity. The output of nitrogen applied annually is disaggregated to the monthly scale so that it can be utilized in the watershed model. It is assumed that each month receives 1/12 of the nitrogen applied as manure while the month of March receives all the nitrogen applied as fertilizer for croplands and the month of August receives all the nitrogen applied as fertilizer for pasture to simply represent seasonal applications of fertilizer. Then, the outflow results produced by HSPF are aggregated from the daily to the annual scale to determine the average annual nitrogen loading.

These scenarios are dramatizations that are developed based on assumptions about human activities within the watershed and using attributes of the Fauquier County database but could be generalized to represent other locations with more complex water quantity and quality issues. In this case, expansions in agricultural industries, specifically crop farming or animal husbandry, are examined because more agricultural land use could be considered more acceptable by the county since it would discourage urban development and maintain the desired rural aesthetic. Since this framework is modeling static conditions within the 1-year simulation period, the agricultural expansion is assumed to have occurred sometime before, rather than during, the simulation period. Furthermore, since these scenarios are not being used to predict conditions during a specific future year, the time value of money is not considered, and it is assumed that monetary valuation remains constant across all scenarios. Thus, money values are in constant base-year prices. Additionally, since water scarcity is not considered to be a major issue in this county, it is not explored in this study. It is also assumed that the population of the county residents does not significantly increase so there is insignificant urban development. In-migrants are assumed to work in the same sectors as the current labor force and increase output only from existing economic sectors. Furthermore, in-migrants who are retired, work outside the county, or are just seasonal residents are not considered. Examples of the I-O data tables utilized in these scenarios are included in Section A.1 of Appendix A.

### 2.5.1 Baseline Scenarios (S1 and S2)

For the baseline scenarios (referred to as S1 and S2 in Table 2-2), the basic I-O model is used to determine how a dramatic increase in production for export from an agricultural sector, represented by an increase in final demand in the y vector, would result in an increase in economic output from that sector, but would also require an increase in use of factors of production, specifically land, labor, water, and applied nitrogen. Thus, the basic I-O model is used to determine how expanding final demand by an amount necessary to fully utilize all land available for agriculture would impact water quality, represented by the concentration of nitrogen outflow from the local watershed. Under S1, demand for crop farming is expanded to achieve a 270% increase in land used for crop farming. Under S2, demand for animal husbandry is expanded to achieve a 220% increase in land used for animal husbandry. In these two scenarios, it is assumed that the increase in land use associated with the expansion of agricultural activity is equally distributed among the HSPF land segments and that land classified as forest in HSPF is converted to cropland under S1 and pasture under S2. Furthermore, the increase in applied nitrogen associated with the expansion of agricultural activity is assumed to increase nitrate deposition in HSPF during the month of March for cropland and during August for pasture to correspond with fertilizer application.

**Table 2-2.** Characteristics of scenarios in Chapter 2

| **Scenario Name** | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| **Economic Model Utilized** | Basic IO | Basic IO | RCOT | RCOT | RCOT | RCOT | RCOT | RCOT |
| **Expanded Economic Sector** | Crop Farming | Animal Husbandry | Crop Farming | Animal Husbandry | Crop Farming | Animal Husbandry | Crop Farming | Animal Husbandry |
| **Choice in Location** | N/A | N/A | Upstream vs Downstream | Upstream vs Downstream | Upstream vs Downstream | Upstream vs Downstream | Upstream vs Downstream | Upstream vs Downstream |
| **Choice in Technology** | N/A | N/A | N/A | N/A | Standard vs Alternative (*33% decrease in nitrogen*) | Standard vs Alternative (*33% decrease in nitrogen*) | Standard vs Alternative (*33% decrease in nitrogen & 20% increase in factor price*) | Standard vs Alternative (*33% decrease in nitrogen & 20% increase in factor price*) |

### 2.5.2 Choice in Location (S3 to S8)

Under S3, S5, and S7, demand for crop farming is increased to achieve a 270% increase in land use as is done under S1. Under S4, S6, and S8, demand for animal husbandry is increased to achieve a 220% increase in land use as is done under S2. The differences among these scenarios are summarized in Table 2-2. Unlike S1 and S2, S3 through S8 utilize RCOT instead of the basic I-O model to evaluate alternatives for alleviating the rising nitrogen concentrations that result from the dramatic increase in production from either crop farming or animal husbandry. In these scenarios, the choice mechanism of RCOT is used to select between two locations to obtain an optimal distribution of agricultural activity. For RCOT, the watershed is comprised of two super-segments, Upstream and Downstream, each comprised of multiple HSPF segments and RCOT specifies how much activity will take place in each individual segment of the two sets of segments shown in Figure 2-4. Thus, the expansion in agricultural activity is no longer assumed to be equally distributed as it was under S1 and S2. Furthermore, these scenarios assume that different factor endowments are available in each location. More land is assumed to be available in Upstream for expansion of agricultural activities than in Downstream. Residential and industrial land use is predominantly located in Upstream along with water withdrawn for residential use, which results in higher excess nutrient concentration in Upstream than in Downstream. As a result, it is assumed that less water is available and less nutrient runoff is allowable from agricultural expansion in Upstream rather than in Downstream.

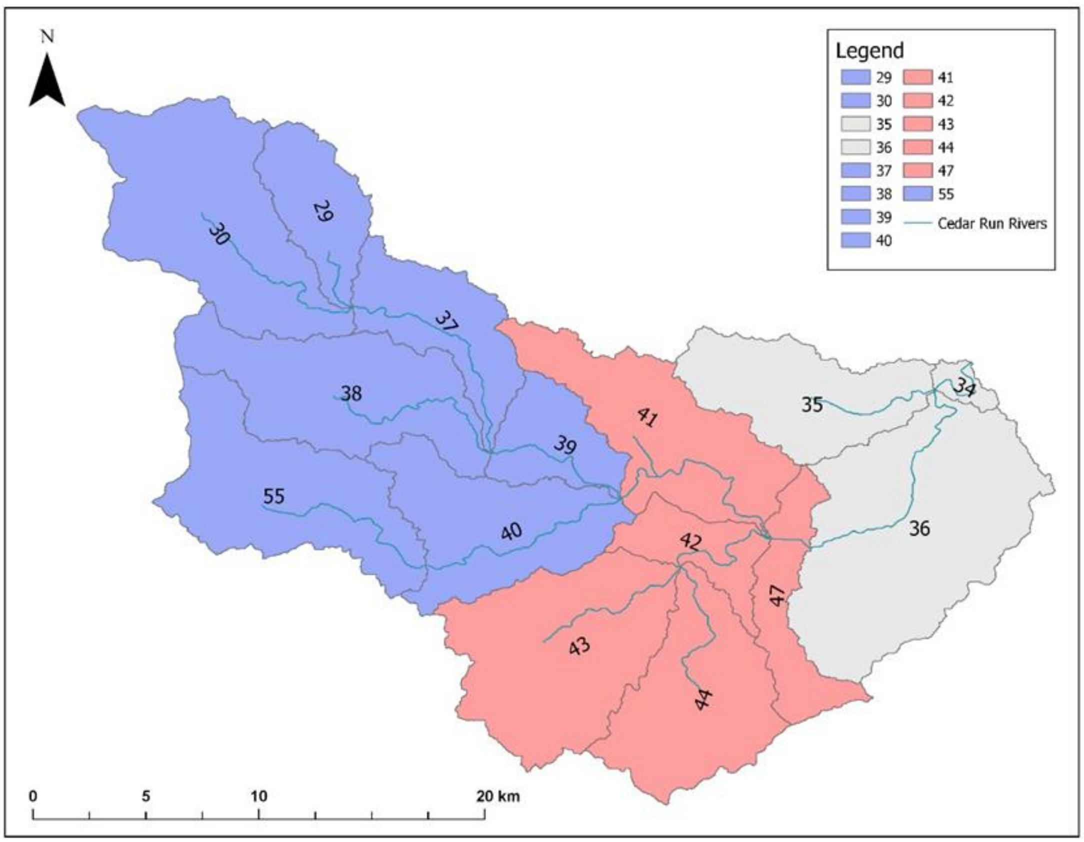


**Figure 2-4.** Cedar Run Watershed with Upstream (blue) defined as segments 29, 30, 37, 38, 39, 40, 55 and Downstream (red) defined as segments 41, 42, 43, 44, 47

### 2.5.3 Choice in Management Practices (S5 to S8)

Under S5 through S8, a choice in practice is incorporated into RCOT in addition to the choice in production location. Under S5 and S6, a hypothetical alternative management practice is introduced, which reduces fertilizer requirements for crop farming and animal husbandry by 33% when compared to baseline conditions. Under S7 and S8, a hypothetical alternative management practice is also introduced into RCOT, which could reduce fertilizer requirements by 33% but the factor price would be 20% more than for the standard practice. Thus, RCOT is used in these scenarios to select between two locations to obtain an optimal distribution of agricultural activity and to choose between two management practices to maximize efficiency.

### 2.5.4 Results

Table 2-3 presents the economic modeling results for each scenario, specifically from the x and φ vectors. Examples of these vectors can be found in Sections A.1.8 and A.1.9 of Appendix A, respectively. These outputs are listed as percent increases relative to the outputs obtained from 2012, the economic base year. When crop farming is expanded under S1, S3, S5, and S7, the acres of cropland increase by 270% regardless of the configuration of the economic model. Additionally, these scenarios also produce similar increases in jobs (~7.8%), water withdrawn (~5.7%), and economic output (~1.8%) within the county. Furthermore, these scenarios also result in a 240% increase in applied nitrogen except for S5, which only results in a 130% increase in applied nitrogen. When animal husbandry is expanded under S2, S4, S6, and S8, the acres of pasture increase by 220% regardless of the configuration of the economic model. These scenarios also produce similar increases in jobs (~2.6%), water withdrawn (3.4%), and economic output (~0.9%) within the county. Additionally, these scenarios result in a 23% increase in applied nitrogen except for S6, which results in a 13% reduction in applied nitrogen.

**Table 2-3.** Percent increases in φ and *x* vector outputs relative to 2012 base year

| Scenario | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 |
|---|---|---|---|---|---|---|---|---|
| **Jobs** | 7.8 | 2.6 | 7.8 | 2.6 | 7.6 | 2.5 | 7.6 | 2.5 |
| **Pasture** | 32 | 220 | 32 | 220 | 32 | 220 | 32 | 220 |
| **Cropland** | 270 | 0.0 | 270 | 0.0 | 270 | 0.0 | 270 | 0.0 |
| **Water Withdrawn** | 5.7 | 3.4 | 5.7 | 3.4 | 5.6 | 3.4 | 5.6 | 3.4 |
| **Nitrogen Applied** | 240 | 23 | 240 | 23 | 130 | -13* | 240 | 23 |
| **Economic Output** | 1.8 | 0.9 | 1.7 | 0.8 | 1.7 | 0.8 | 1.6 | 0.8 |

*This table has been revised from the table that was originally published in *Frontiers in Water*

When the output results for land use and applied nitrogen (Table 2-3) are transferred from the economic model to HSPF (see Sections A.2 and A.3 of Appendix A), the total nitrogen concentration in watershed outflow from Cedar Run Watershed is obtained based on HSPF output results aggregated to the annual scale (see A.4 of Appendix A). Table 2-4 presents the nitrogen concentrations achieved by each scenario. When crop farming is expanded under S1, nitrogen concentration in the watershed increases from 0.6 to 4.3 mg/L and when animal husbandry is expanded under S2, nitrogen concentration increases from 0.6 to 0.7 mg/L. When RCOT is only used to determine optimal distribution of agricultural activity, nitrogen concentration increases from 0.6 to 4.2 mg/L under S3 and from 0.6 to 0.7 mg/L under S4. When RCOT is used to select the most efficient management practice among the two considered, in addition to spatial distribution of agricultural activity, nitrogen concentration increases from 0.6 to 2.2 mg/L for S5 and from 0.6 to 0.7 mg/L for S6. When a higher factor price becomes associated with the alternative practice, nitrogen concentration increases from 0.6 to 4.2 mg/L for S7 and from 0.6 to 0.7 mg/L for S8.

**Table 2-4.** Concentration of total nitrogen in watershed outflow (mg/L)

| **2012 Watershed Concentration** | 0.6 | | | |
|---|---|---|---|---|
| **Crop Farming Expansion** | **S1** | **S3** | **S5** | **S7** |
| | 4.3 | 4.2 | 2.2* | 4.2 |
| **Animal Husbandry Expansion** | **S2** | **S4** | **S6** | **S8** |
| | 0.7 | 0.7 | 0.7 | 0.7 |

*This table has been revised from the table that was originally published in *Frontiers in Water*

## 2.6 Discussion

An increase in economic demand caused by an expansion of crop farming results in an increase in jobs that is about three times larger than what results from an expansion of animal husbandry. Additionally, the crop farming expansion results in a 1.8% increase in economic output, which is about double the increase in economic output that results from the expansion in animal husbandry (0.9%). These results are achieved regardless of whether the basic I-O or RCOT model is used. Therefore, an expansion in crop farming would be more desirable than an expansion in animal husbandry when examining these scenarios from an economic perspective.

In addition to higher increases in jobs and economic output, a crop farming expansion also results in a slightly higher increase in annual water withdrawal than an animal husbandry expansion, but both increases in water withdrawal are considered insignificant when compared to the quantity of water available within Cedar Run Watershed. However, the crop farming expansion also results in a significantly higher increase in fertilizer applied annually within the watershed than the animal husbandry expansion. As a result, the crop farming expansion increases the concentration of nitrogen in Cedar Run Watershed by 3.7 mg/L under S1 while the animal husbandry expansion has insignificant effects on nitrogen concentration under S2. Thus, while a crop farming expansion results in a higher increase in jobs, it also results in a significantly higher application of nitrogen and a significantly higher impact on the nitrogen outflow concentration than an animal husbandry expansion. Therefore, an expansion of animal husbandry would be more acceptable than a crop farming expansion when analyzing these results from an environmental perspective.

The results from S1 and S2 demonstrate the trade-offs associated with expansions in crop farming or animal husbandry. The results from S3 through S8 indicate how choices made within the economic system could alleviate the severity of the nitrogen loading. When the choice between Upstream and Downstream is implemented using RCOT, the resulting nitrogen concentration under S3 is insignificantly lower than under S1. However, when choice in management practice is implemented under S5, the resulting nitrogen concentration from crop farming expansion reaches only 2.2 mg/L at the outflow of Cedar Run Watershed, which is about 50% lower than under S1 when only the standard technology can be applied, because RCOT selects the alternative practice as the most efficient solution. Therefore, alternative technologies appear to be more effective at alleviating water quality issues than optimal spatial distribution of economic activity. However, when factor price associated with the alternative practice is increased to 120% of the standard practice cost under S7, RCOT selects the standard practice over the alternative practice as the most efficient solution in that case. As a result, the corresponding nitrogen concentration is as high as it is under S3. Thus, when a more resource-efficient practice is introduced as an alternative during expansions in either crop farming or animal husbandry, this practice is selected by RCOT because it requires less fertilizer, which results in a lower increase in nitrogen concentration from expanded crop farming. However, when the alternative practice is introduced with a higher factor price, RCOT selects the standard practice because it is the more cost-effective option and factor constraints are not binding in this scenario. Interestingly, the introduction of alternative choices has little impact on the increase in nitrogen concentration that results from animal husbandry expansion because this economic sector already utilizes significantly less fertilizer than the crop farming sector. The nitrogen concentration resulting from animal husbandry expansion remains at around 0.7 mg/L, regardless of the choices considered by RCOT. Therefore, implementing the alternative practice within the animal husbandry sector may be unnecessary in terms of alleviating impacts on water quality.

### 2.6.1 Conclusions

A framework that couples economic and watershed systems can capture the interactions between these two systems and can also be used to analyze how changes in economic activity will impact watershed health. However, selecting the appropriate economic model requires careful consideration and more detailed information could be obtained depending on which model is utilized. When the basic I-O model is coupled with HSPF, we can capture the changes in water quality associated with an expansion in economic activity. However, when RCOT is coupled with HSPF, more detailed information can be obtained about how choices in spatial location or technology could influence economic activity and alter impacts on watershed health. These are realistic decisions that may be made within the economic system and, by linking RCOT with HSPF, the environmental impacts of these choices can be examined.

### 2.6.2 Future Work

Building on the modular framework, future work will involve designing more complex scenarios that can evaluate policy options and regional planning decisions. The simple example presented in this paper focuses primarily on the influence of the economic system on the natural system, but in the future, scenarios will be developed that look more closely at how the natural system affects the economic system and that will couple the models more intimately. Additionally, this modular framework should also be applied in a more complex location with a greater number of economic sectors of interest and pressing environmental concerns. The multi-region capabilities of WTM/RCOT could also be explored in a region located within a watershed that spans multiple economic systems. The modular framework is also appropriate for a system-of-systems approach that integrates a variety of models from different disciplines and modeling paradigms to represent a socio-environmental (or social-ecological) system, and that can be used to inform policy and decision-making processes (Iwanaga et al., 2021; Little, Hester, & Carey, 2016; Little et al., 2019).

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# Chapter 3 Applying a coupled hydrologic-economic modeling framework: Evaluating alternative options for reducing impacts for downstream locations in response to upstream development

Maria Amaya[1], Faye Duchin[2], Erich Hester[1], John C. Little[1]

[1]Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, Virginia, USA

[2]Department of Economics, Rensselaer Polytechnic Institute, Troy, New York, USA

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## 3.1 Abstract

Economic input-output and watershed models provide useful results, but these kinds of models do not use the same spatial units, which typically limits their integration. A modular hydrologic-economic modeling framework is designed to couple the Rectangular Choice-of-Technology (RCOT) model, a physically constrained, input-output (I-O) model, with the Hydrological Simulation Program-Fortran (HSPF). Integrating these two models can address questions relevant to both economists and hydrologists, beyond addressing only administrative or watershed concerns. This framework is utilized to evaluate alternative future development prospects within Fauquier County, northern Virginia, specifically residential build-up, and agricultural intensification in the upstream location of the local watershed. Illustrative scenarios are designed to evaluate downstream impacts on watershed health caused by upstream development and changes made within the economic sectors in response to these impacts. In the first case, an alternative residential water technology is more efficient than the standard for ensuring adequate water supply downstream. For scenarios involving upstream agricultural intensification, a crop shift from grains to fruits and vegetables is the most efficient of the alternatives considered. This framework captures two-way feedback between watershed and economic systems that expands the types of questions one can address beyond those that can be analyzed using these models individually.

**Keywords:** modeling, framework, economic, hydrologic, watershed, spatial, downstream

## 3.2 Introduction

The economic input-output (I-O) model was extended to include environmental data by Leontief [1] to evaluate the pollution generated because of consumption and production associated with economic activity. Environmentally extended, input-output (EEIO) databases have subsequently been used to assess environmental impacts, such as waste generation, land use, and water use, throughout the world. However, the majority of EEIO applications have focused on national-level assessments, which limits their usefulness in assessing local impacts [2]. As a result, the number of regional I-O studies has been growing, reflecting a desire to perform economic analyses at the sub-national level [3].

Originally developed to analyze the trade flows among regions smaller than nations, as described by Miller and Blair [4], multiregional input-output (MRIO) analysis has also been used to quantify environmental impacts that result from the economic activity and trade occurring simultaneously across these multiple regions. Guo and Shen [5] applied an MRIO model to the provinces of China to evaluate water use in the agricultural sector of the economy. Other regionalized input-output approaches have been utilized to evaluate resource extraction among environmental effects at a spatial scale defined by administrative boundaries. For example, Dilekli and Duchin [6] applied the World Trade Model (WTM), an inter-regional trade I-O model based on the Theory of Comparative Advantage developed by Duchin [7], to thirteen states in the northeastern United States to evaluate the potential for biofuel production in these locations while minimizing resource use. However, spatially explicit EEIO databases that are distinguished by watershed criteria rather than regional administrative boundaries are also important when assessing the local environmental impacts of regional economic activity, especially when evaluating the effects on water resources. While water pollution is often regarded as a local environmental issue, a watershed may span many regions, which necessitates the consideration of both the locations of water extraction and release [8]. The localized impacts of new economic activity on watershed health may vary depending on the spatial location of the new activity. These changes in economic activity will also have effects further downstream in the watershed.

I-O models do not typically have a need to represent spatially distributed water resource systems and most economic models of natural resource use are spatially lumped [9]. However, interest in incorporating spatially explicit information into EEIO databases has greatly increased as demonstrated by an increase in spatially explicit I-O studies in the past decade [2]. The WTM model was used by Lopez-Morales and Duchin [10] to evaluate water withdrawal policies and their economic implications for thirteen hydro-economic regions in Mexico. Lutter, Pfister [11] conducted a spatially explicit MRIO analysis to represent virtual water flows within and between countries at the watershed scale. Analyzing economic activity at the water basin scale is more appropriate to inform policies for water extraction and pollution than utilizing spatial scales defined by purely administrative boundaries. However, there are limitations in the feasibility of these types of datasets for I-O modeling. It is difficult to create spatial maps for industrial sectors because many land classification systems cannot locate the secondary and tertiary sectors present within an economic system. I-O databases are also typically unable to reproduce hydrologic complexity since databases with only economic information need to be supplemented with additional information to address water-related questions, but a more accurate distribution of environmental impacts can be achieved through linkage to a spatially explicit watershed model [2, 12]. Thus, coupling an I-O model with a spatially distributed watershed model, calibrated using local monitoring data, can provide insight into the spatial units most suitable for addressing questions of interest to both economists and hydrologists.

### 3.2.1 Study Location

This paper investigates a regional economy, its local impacts on a watershed that lies within that region, and the human decisions made within the economic system in response to those impacts. The region of study is Fauquier County, located in northern Virginia in the United States. This county is predominantly rural with farmland representing approximately 54% of the county land area. During the 20$^{th}$ century, the cattle industry was prominent in the county, but the number of farms focused on cattle production declined between 1997 and 2012 from 50% to 35%, respectively because of a shift from animal husbandry to crop farming occurring within the agricultural sector. Between 2002 and 2012, the number of full-time farmers decreased by 24% while the number of part-time farmers increased by 14% as the county experienced an increase in small acreage farms and specialty operations. While Fauquier County has long been associated with agricultural production, it has also been experiencing development pressure due to its proximity to the Washington DC metropolitan area. County officials are interested in supporting the agricultural sector of the economy by preserving farmland and avoiding sprawling residential development. As a result, 90% of the county is zoned for agricultural development while residential development is currently confined to Service Districts [13, 14].

Located within Fauquier County is Cedar Run Watershed (498 $km^2$), a sub-basin of Occoquan Watershed (1,515 $km^2$) located 50 km southwest of Washington DC. Occoquan Watershed drains into the Occoquan Reservoir, which serves as a source of drinking water for around two million residents in northern Virginia. Since algal blooms used to be frequent in this watershed, nutrient enrichment, specifically nitrogen and phosphorus, and eutrophication are considered primary water quality concerns. Population growth and rapid urbanization are also of concern for Occoquan Watershed. To address these issues, both volume of flow and water quality data have been continuously measured at monitoring sites throughout the watershed by the Occoquan Watershed Monitoring Laboratory (OWML) since 1973 [15]. The Occoquan Policy was also established to regulate water quality within the Occoquan Reservoir. Following these regulations, if the ambient nitrate concentration exceeds 5.0 mg/L (as nitrogen) in the Occoquan Reservoir, then nitrogen removal facilities must be operated. Nitrogen concentration must also be below 1.0 mg/L in sewage effluent within Occoquan Watershed [16]. Thus, future development prospects must be carefully considered within Cedar Run Watershed, which currently contains forest, agricultural land use, and minimal residential development, to limit their downstream impacts.

### 3.2.2 Research Objectives

Alternative future development prospects that may occur within Fauquier County are examined along with their impacts on downstream water quality within Cedar Run Watershed at an average annual time scale. The influence of these impacts on human decisions made within different sectors of the local economy are also examined. Specifically, elevated nitrogen concentrations and increased water withdrawal within the watershed, caused by upstream residential build-up or agricultural intensification, are evaluated under several scenarios. To conduct this analysis, the modular hydrologic-economic modeling framework, conceptualized in [17], is utilized to demonstrate that it can capture the interactions between economic and watershed systems at a finer spatial resolution than either administrative boundaries or watershed criteria, which expands the type of questions that may be addressed by either of the models coupled in this framework.

The RCOT model, a physically constrained, I-O model, is used to represent the economic system. This model can represent the entire economy of Fauquier County as distinct and interdependent industrial sectors and can represent the economy in terms of physical phenomena, such as material flows of goods, rather than just monetary values, which allows for straightforward transfer of information between the economic and watershed systems. RCOT also has the distinctive capability to select among choices of technology introduced within different economic sectors to maximize efficiency, which is achieved by constraining factor use to not exceed the available endowment (physical constraint) or a policy constraint [18]. Thus, changes in human decisions and technological innovation in response to environmental conditions may be observed within the different economic sectors.

To represent the watershed system, HSPF is used. HSPF is a semi-distributed model that divides the watershed into land segments that are defined as the total land area that contributes water flow to a channel reach. These amorphic segments give HSPF lumped-parameter characteristics, but each segment represents the distinct hydrological processes that are distributed throughout the watershed, which also gives HSPF characteristics of a spatially distributed model [19]. While there are other, more fully distributed watershed models, HSPF has a long history of application in Cedar Run Watershed. This model has already been calibrated to represent the hydrologic behavior of Cedar Run Watershed by OWML using local weather data, including regional cloud cover, wind speed, air temperature, dew point temperature, and precipitation, collected from 2008 to 2010. The watershed model was then validated using local data collected from 2011 to 2012 [20, 21]. By coupling an economic model with the attributes of RCOT with a distributed watershed model like HSPF, the localized impacts of new economic activity on watershed health can be analyzed at the sub-basin scale along with how these impacts influence choices made within the different economic sectors. In summary, the following questions are addressed in this paper:

1. Can RCOT's selection among technologies for residential water use alleviate the downstream impacts on water quantity and nitrogen concentration caused by upstream residential build-up in Cedar Run Watershed and modeled using HSPF?
2. Can RCOT's selection among crops alleviate the downstream impacts on water quantity and nitrogen concentration caused by upstream agricultural intensification in Cedar Run Watershed and modeled using HSPF?
3. Does coupling a distributed watershed model with a physically constrained, I-O model provide two-way feedback that captures the interactions between the watershed and economic systems at a level of spatial detail that expands the types of questions that may be addressed by either of the models coupled in this framework?

## 3.3 Materials and Methods

### 3.3.1 HSPF

HSPF is a deterministic, physically based model designed to continuously simulate a variety of water quantity and quality processes that occur within a watershed at the daily timestep. In this model, the watershed is represented as a set of constituents, including water and nutrients, that interact with each other as they move through a fixed environment. The watershed is subdivided into different types of elements, which are composed of zones and nodes. Zones are defined as discrete portions of the environment and are typically associated with the integral of a spatially variable quantity. In contrast, nodes are defined as points in space, which can be used to define the boundaries of zones and may be associated with a specific value of a spatially variable function. Thus, the relationship between zones and nodes corresponds to the relationship between the definite integral of a function and its values at the limits of integration. Bicknell, Imhoff [22] provide more information on these relationships and the parameters utilized by HSPF.

There are two element types utilized by HSPF: channel reaches and land segments. Elements that are categorized as the same type encompass the same nodal arrangement and utilize the same set of parameters although there can be variation in parameter values. Channel reaches are one-dimensional elements that are composed of a single zone situated between two nodes (see Figure 3-1). Parameters, such as flow rate, are simulated at these nodes, while zones are associated with storage values that receive inflows and disperse outflows. Land segments are defined as discrete land areas with uniform soil properties and similar hydrological characteristics. These elements do not have any nodes and are represented by a set of zones, such as the soil surface layer, subsurface soil layers, and the groundwater table, in which constituents can accumulate. These constituents, including water and nitrogen, move from one land segment to a downslope segment or channel reach.

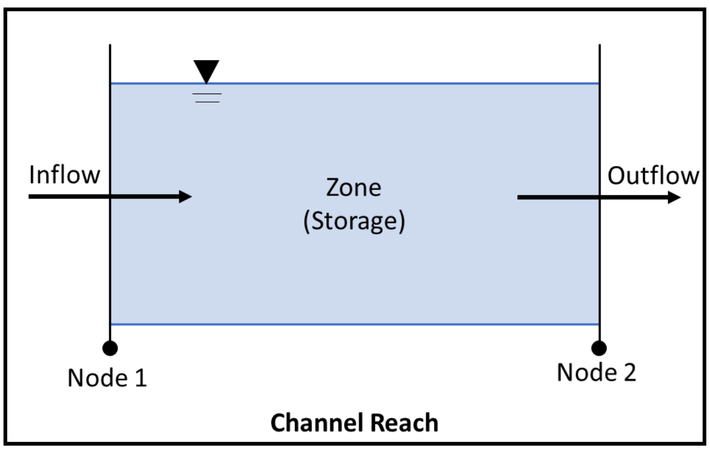


**Figure 3-1.** The zones and nodes that compose the element type called Channel Reach

HSPF utilizes application modules to facilitate the modeling of both water quality and quantity processes that occur within the different types of elements. Each of these application modules contains sub-modules that model the processes that occur within the associated element types. For example, the module PERLND models the permeable land segments while RCHRES models the channel reaches. The following continuity equation is utilized by the sub-module HYDR of RCHRES to model changes in the surface water volume of each channel reach over time with water withdrawn and precipitation being exogenously defined [22]:

$$\frac{d}{dt}V = \mathbf{V_{in}} - \mathbf{V_{out}} + \mathbf{P} - \mathbf{E} - \mathbf{W} \tag{3.1}$$

where,

V = stored surface water volume, $V_{in}$ = volume of inflow, $V_{out}$ = volume of outflow, P = precipitation volume, E = evapotranspiration volume, W = water withdrawn

The PQUAL sub-module in PERLND models the deposition and movement of nitrogen through the soil of permeable land areas, with nitrogen deposition being exogenously defined, and can be represented with the following basic mass balance equation [22]:

$$\frac{d}{dt}N = \mathbf{N_{in}} - \mathbf{D} - [\mathbf{N_{OL}} + \mathbf{N_{SED}} + \mathbf{N_{I}} + \mathbf{N_{GW}}] \tag{3.2}$$

where,

N = nitrogen stored in the soil of permeable land area, $N_{in}$ = nitrogen deposition, D = nitrogen removed by decay, $N_{OL}$ = nitrogen removed by overland flow, $N_{SED}$ = nitrogen removed by detached sediment, $N_{I}$ = nitrogen removed by interflow, $N_{GW}$ = nitrogen removed by active groundwater

HSPF also has utility modules that link the application modules and manage data. These modules utilize data that are input as time series into HSPF, such as precipitation and withdrawn water, to generate additional time series as output. HSPF also uses the SCHEMATIC module to exogenously define the size and composition of each land segment [22].

For the scenarios analyzed in this paper, Cedar Run Watershed is divided into an upstream region and a downstream region. The upstream region is composed of Segments 29, 30, 37, 38, 55, 40, and 39, while the downstream region is composed of Segments 41, 42, 43, 44, and 47. These segments are recognized within the HSPF model calibrated by OWML to represent Cedar Run Watershed and are displayed in Figure 3-2.

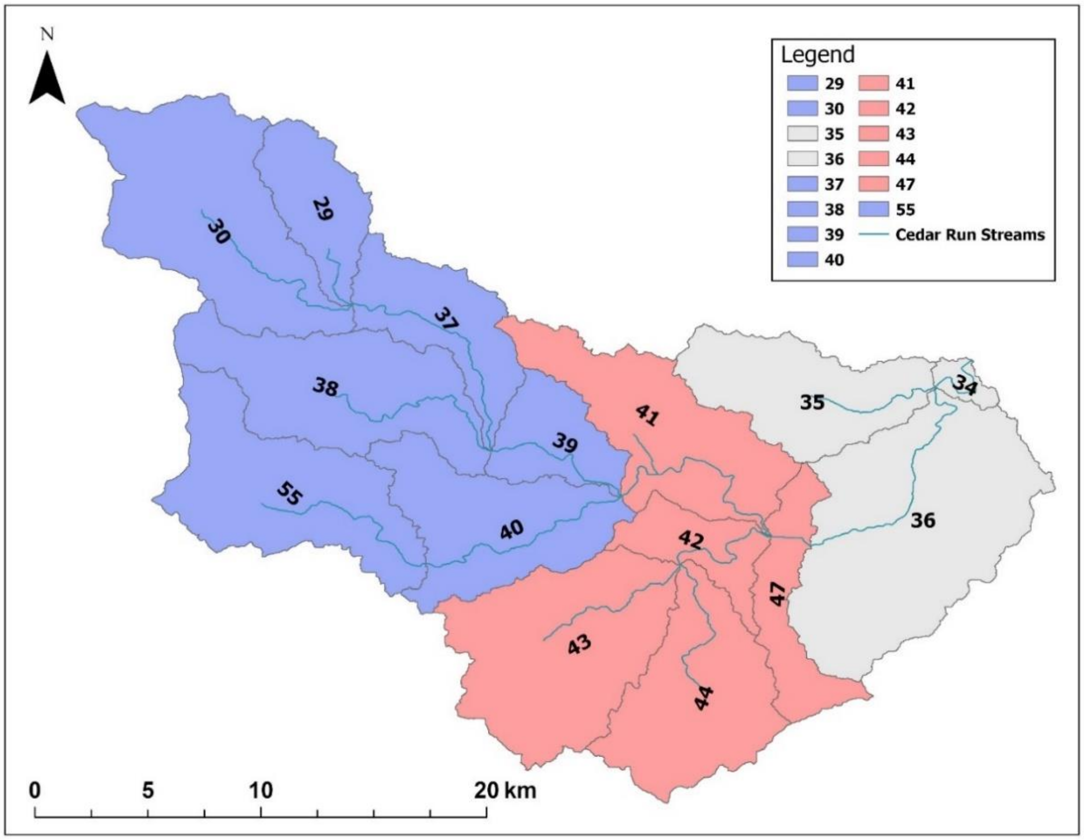


**Figure 3-2.** Cedar Run Watershed divided into numbered segments, including Upstream (blue), Downstream (red), and segments that lie outside of Fauquier County (gray) [17]

### 3.3.2 RCOT

As an extension of the basic I-O model, RCOT is composed of two components: the primal quantity model and the dual price model. The primal model calculates economic output (x) and factor use (φ) for an economy composed of *n* sectors and *k* factors of production in physical, monetary, or mixed units [18]. Factors of production are required inputs that are not produced themselves, such as labor, capital, and land. Additional resources have also been included as factors of production in previous I-O studies, such as water [23] and nitrogen [24]. The basic I-O model utilizes square, invertible matrices that are defined by the *n* economic sectors in the primal model, which is a feature that is retained in the MRIO and EEIO sub-fields. Distinctively, RCOT is a linear program that can select among choices in operational technologies to satisfy specific factor constraints. The primal model of RCOT specifies *t* technologies for the *n* economic sectors where $t \geq$

*n*. As a result, parameters and variables are distinguished among alternative technologies as well as economic sectors, which makes the matrices rectangular rather than square. Duchin and Levine [18] provide more detail on the logic utilized by RCOT. The following equations are used by the primal model in RCOT (augmented variables are denoted with an asterisk):

$$(\mathrm{I}^* - \mathrm{A}^*)\mathrm{x}^* = \mathrm{y} \rightarrow \mathbf{x}^* = (\mathbf{I}^* - \mathbf{A}^*)^{-1}\,\mathbf{y} \tag{3.3}$$

$$\varphi = \mathrm{F}^*\mathrm{x}^* \rightarrow \boldsymbol{\varphi} = \mathbf{F}^*(\mathbf{I}^* - \mathbf{A}^*)^{-1}\mathbf{y} \tag{3.4}$$

where,

$A^*$ = coefficient matrix $(n \times t)$, $F^*$ = matrix of factor requirements per unit of output $(k \times t)$, $y$ = final demand vector $(n \times 1)$, $x^*$ = economic output vector $(t \times 1)$, $I^*$ = identity matrix $(n \times t)$, $\varphi$ = factor use vector $(k \times 1)$

Each economic sector has specific factor requirements to produce one unit of output, which are included in the $F^*$ matrix. The primal model utilizes an objective function that minimizes factor use while ensuring that factor use does not exceed factor availability (f) and production still satisfies final demand (y). If the required factor endowments are not sufficient to meet the specified final demand, then there would be no feasible solution for the scenario. This objective function is as follows:

$$\text{Minimize } \boldsymbol{M} = \boldsymbol{\pi}'\mathbf{F}^*\mathbf{x}^* \tag{3.5}$$

$$\text{such that } (\mathbf{I}^* - \mathbf{A}^*)\mathbf{x}^* \geq \mathbf{y} \text{ and } \mathbf{F}^*\mathbf{x}^* \leq \mathbf{f}$$

where,

$x^*$ = economic output vector $(t \times 1)$, $y$ = final demand vector $(n \times 1)$, $A^*$ = coefficient matrix $(n \times t)$, $f$ = factor endowments vector $(k \times 1)$, $F^*$ = matrix of factor requirements per unit of output $(k \times t)$, $\pi$ = vector of factor prices $(k \times 1)$

The dual price model calculates the unit cost (p) associated with each economic sector based on the prices associated with each factor of production ($\pi$). The following equation is used by the dual price model in RCOT:

$$\mathbf{p} = (\mathbf{I}^* - \mathbf{A}^{*\prime})^{-1}\mathbf{F}^{*\prime}\boldsymbol{\pi} \tag{3.6}$$

where,

$\pi$ = vector of factor prices (k × 1), p = sectoral price vector (n × 1), $A^{*\prime}$ transpose of matrix $A^*$, $F^{*\prime}$ = transpose of matrix $F^*$

The dual price model seeks to maximize the money value of final demand minus scarcity rents on fully utilized factors of production using the following objective function:

$$\text{Maximize } \boldsymbol{W} = \mathbf{p}'\mathbf{y} - \mathbf{r}'\mathbf{f} \tag{3.7}$$

$$\text{such that } (\mathbf{I}^* - \mathbf{A}^*)'\mathbf{p} \leq \mathbf{F}^{*\prime}(\boldsymbol{\pi} + \mathbf{r})$$

where,

y = final demand vector (n × 1), $A^*$ = coefficient matrix (n × t), $I^*$ = identity matrix (n × t), f = factor endowments vector (k × 1), $F^*$ = matrix requirements per unit of output (k × t), p = sectoral prices vector (n × 1), r = factor scarcity rents vector (k × 1)

At the optimal solution, the two objective functions displayed in Equations 3.5 and 3.7 are equal, which indicates that the total cost is equal to the sum of factor costs plus any rents. A change in the availability or unit price of a resource can change the choice selection among the technologies available to the different sectors [18].

### 3.3.3 Building the Economic Database

While OWML has already calibrated HSPF parameters to represent Cedar Run Watershed using local monitoring data, an economic database representative of Fauquier County had to be constructed for use in RCOT. To construct the database for this study, sectoral economic data, representative of base year 2012, are obtained for Fauquier County. 2012 was selected as the base year because the most complete database that could be assembled for this county is representative of this year. Monetary county-level, input-output data and industry final demand data based on national accounts are provided by a private company called IMPLAN Group, LLC [25]. To compile their I-O datasets, IMPLAN obtains data from different government sources and provides estimates for unavailable data, which are gauged against other data to verify for accuracy.

The I-O data obtained from IMPLAN are aggregated, following the guidelines provided in [26], into seven basic industrial sectors: agriculture, mining, construction, manufacturing, utilities, professional services, and government services. These sectors are aggregated based on the North American Industry Classification System (NAICS) recognized by the United States Census Bureau [27]. Then, the agriculture sector is disaggregated into three sectors for more detailed analysis of agricultural activity as was done by Julia and Duchin [28]: crop farming, animal husbandry, and other agricultural activities. Once this I-O data are incorporated into RCOT, the model is run for the 2012 base year to calculate the economic output associated with each of the industrial sectors. The output results produced by RCOT are then examined to verify that the model reproduces the sector output data provide by IMPLAN and ensure that this model accurately represents the Fauquier County economy. Finally, to prepare RCOT for analyzing residential build-up, a tenth sector is added to the model to represent the residential sector, which only distributes factors of production to final demand. Since the $y$ vector can be represented in mixed units, the total annual water demand associated with the local population is calculated based on the estimated demand reported by Hickey [29], 140 gal/capita/day, and this value is included as the final demand associated with the residential sector. Thus, Fauquier County is represented in the economic system as ten distinct sectors (nine industrial sectors and one residential sector).

To build the $F^*$ matrix for Fauquier County's factor requirements per unit of output, six factors of production are identified as requirements for the economic sectors: labor, capital, land, water withdrawn, nitrogen applied as fertilizer produced outside of the county, and nitrogen applied as manure produced by the livestock in the animal husbandry sector. Sectoral data for labor, capital, and economic output, provided by IMPLAN, are used to calculate annual labor and capital requirements. Sectoral land requirements are determined using zoning data provided by the Fauquier County GIS Office [30] and land cover data obtained from the Virginia Geographic Information Network [31]. Water withdrawal requirements are determined for each industrial sector using data obtained from an I-O database compiled by the Green Design Institute at Carnegie Mellon University [32] and county water data available from the United States Geological Survey [33]. Agricultural nitrogen requirements are assumed based on county data available from the National Agricultural Statistics Service (NASS). Residential requirements for nitrogen as fertilizer are calculated based on application rates of fertilizer to lawns determined by Law, Band [34], specifically 27.8 kg N/ha of residential land/yr.

### 3.3.4 Coupled Modular Framework

The coupled modeling framework utilized in this study is described in [17], but will be briefly summarized in this sub-section. To manage the different scenarios, the HSPF model representing Cedar Run Watershed is run using URUNME, a recently developed integrated modeling software application, which is used as a user interface to help facilitate the transfer of information between the two models [35, 36]. HSPF is first run under baseline conditions, making no changes to the physical and meteorological characteristics that were calibrated for the watershed using the data collected from 2008 to 2012, before aggregating the resulting water outflow and nitrogen loading to the average annual timestep. This information is used to estimate the factor endowments available for economic activity, specifically land, water, and nitrogen, within the f vector of the economic model. The annual final demand associated with specific economic sectors in the y vector is also adjusted for the scenario being examined before the economic model is run. The resulting output from the φ vector of the economic model provides the factors quantities used to meet final demand. Information from the φ vector regarding changes in land use, water withdrawn from channel reaches, and nitrogen deposition is transferred to the SCHEMATIC, RCHRES, and PERLND modules of HSPF, respectively. Once the changes in land use, water withdrawn, and nitrogen deposition have been transferred from the economic model to the modules of HSPF, the watershed model is run once more to generate results for the scenario being examined. The new results produced for volume of watershed outflow and nitrogen loading are then aggregated to the average annual timestep.

Figure 3-3 provides a basic visual representation of the interactions between the economic and watershed systems. The watershed system, modeled using HSPF, is divided into upstream and downstream regions. Water flows from the upstream to the downstream region, transporting nitrogen and other pollutants in the process. Meanwhile, the economic system in the upstream region, which is the only location where economic activity is expanded for the scenarios analyzed in this study (see Table 3-1), captures the interdependencies between consumption and production as well as among sectors dependent on each other's outputs, such as those shown in Figure 3-3. The economic system generates the economic output necessary to achieve the final demand associated with each sector. However, specific quantities of factors are used to produce that economic output. Changes in water withdrawal, land use, and total nitrogen application also result in changes within the watershed system.

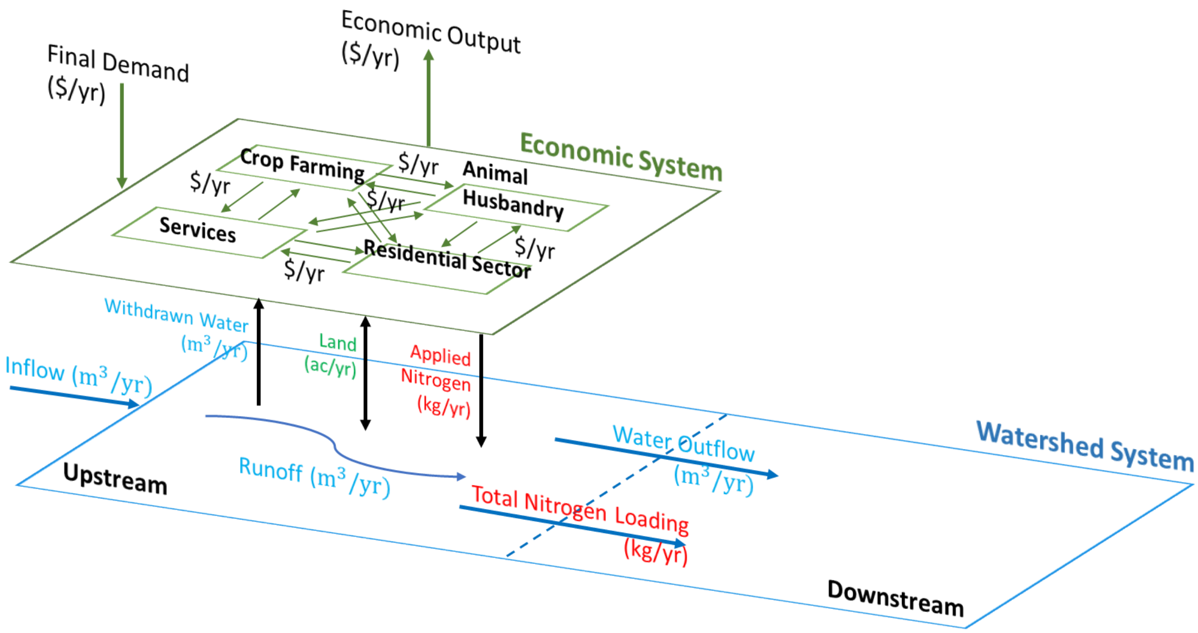


**Figure 3-3.** New economic activity lies in the upstream region and affects downstream watershed health. Note: **green arrows** refer to consumption and production flows within the economic system, **blue arrows** refer to flow of constituents through the watershed system, and **black arrows** refer to interactions between the two systems caused by factors of production

The quantity of water used by the economic system is withdrawn in the upstream region, which reduces the quantity of water that flows downstream. Water withdrawn (W) is exogenously input as a time series into HSPF, populated with water withdrawal data obtained from the φ vector of RCOT. The stored water volume (V), determined by HSPF using Equation 3.1, is obtained from Segment 39 under baseline conditions and aggregated to the annual scale before being input into the f vector of RCOT. The source of nitrogen used by the economic system is applied as fertilizer or manure in the upstream region, which increases the nitrogen loading in the downstream region. Sceptic waste is not considered in these scenarios. Nitrogen deposition ($N_{in}$) is exogenously input as a monthly deposition rate into HSPF based on the nitrogen application data obtained from the φ vector. It is assumed that nitrogen from fertilizer is applied as nitrates ($NO_3^-$) and nitrogen from manure is applied as ammonia ($NH_3$). The total nitrogen removed from the soil of the permeable land area by outflow, determined by HSPF using Equation 3.2, is obtained from Segment 39 under baseline conditions, aggregated to the annual scale, and used to determine the allowable quantity of nitrogen applied in the f vector.

Each land segment of the watershed is also divided into different land use categories, defined based on soil permeability. Changes in land used by the economic sectors also translate into changes in area associated with these different categories and are exogenously defined within the watershed system. The total land available for development in the upstream segments under baseline conditions is transferred from SCHEMATIC to the f vector of RCOT. When a scenario is run, the land use information from the φ vector is used to adjust the land use composition of each segment in SCHEMATIC. Figure 3-4 displays the factors of production utilized by sectors of the economy, specifically crop farming, animal husbandry, the residential sector, and professional services, which are sectors that will be examined in the scenario analysis. These sectors are associated with cropland, pasture, low-density residential land use, and institutional land use, respectively, which are categories defined within the watershed system modeled using HSPF.

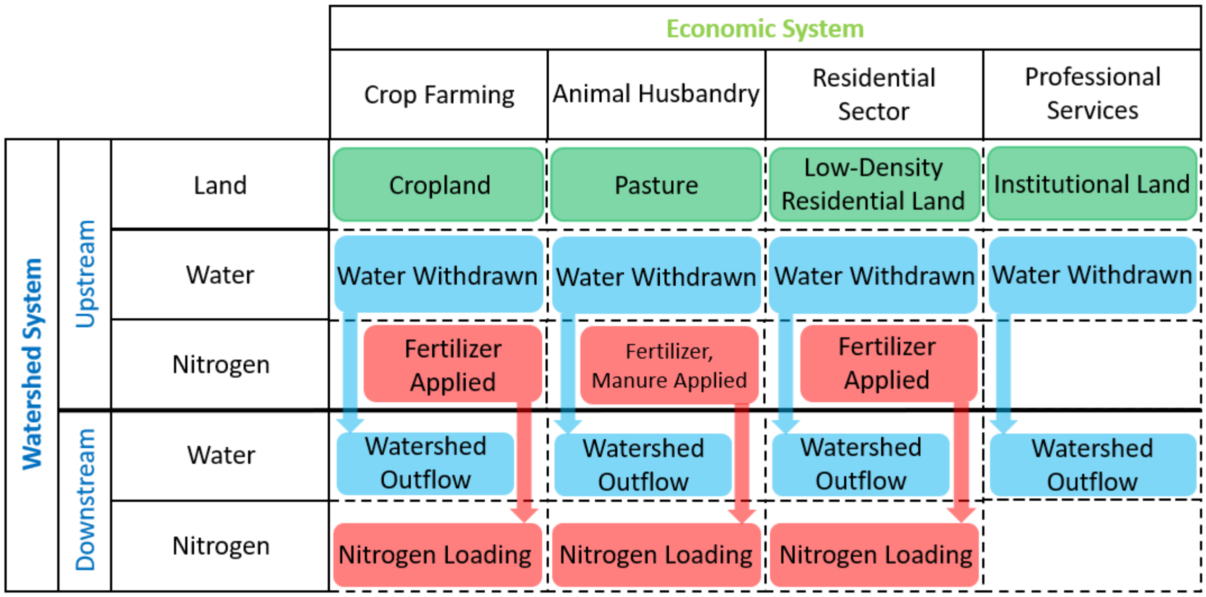


**Figure 3-4.** Factors of production (land, water, nitrogen) are utilized by economic sectors in the upstream region and affect downstream watershed outflow and nitrogen loading

### 3.4 Scenarios

An economic database is constructed to represent Fauquier County using input-output data from 2012 (see Section 3.3.3). Additionally, local monitoring data were collected from 2008 to 2012 by OWML to calibrate and validate an HSPF model to represent Cedar Run Watershed [21]. Utilizing this data in the coupled hydrologic-economic framework described in Section 3.3, a set of four scenarios are designed to determine the localized impacts of upstream human development on watershed health. Specifically, the impacts of upstream residential development are compared to the impacts of upstream agricultural intensification on water quantity and nitrogen concentration within the watershed.

The scenarios developed for this study are characterized in Table 3-1 and will be described in more detail in the following sub-sections. They are dramatizations based on assumptions about future human activities within Cedar Run Watershed and are developed using the Fauquier County database. The quantity of water required for new economic activity is assumed to be extracted from the surface water available in all the upstream segments of the watershed. To determine the allowable quantity of water that can be extracted from the watershed without damaging the ecosystem, the environmental flow requirements are calculated for each channel reach following the process described by Smakhtin, Revenga [37]. These values are assumed to be the minimum flow necessary to maintain the ecological health of each watershed segment and are subtracted from the average annual outflow from each segment [37]. New upstream agricultural activity is assumed to use surface water irrigation so that the amount of water being removed from the watershed would increase by several orders of magnitude when compared to base year conditions, which made future conditions within the watershed more extreme but still plausible for Fauquier County. These scenarios are designed for Fauquier County, but they are used to demonstrate the capabilities of the coupled modeling framework, which is intended to be generalizable so it can be used to represent other locations with different environmental issues. Examples of the I-O data tables utilized in this scenario analysis are provided in Section B.1 of Appendix B.

**Table 3-1.** Characteristics of scenarios in Chapter 3

| Scenario Name | S1 | S2 | S3 | S4 |
|---|---|---|---|---|
| **Scenario Description** | Upstream Residential Build-Up | Upstream Residential Build-Up | Upstream Agricultural Intensification | Upstream Agricultural Intensification |
| **New Technologies are added to this Sector:** | Residential Sector | Residential Sector | Crop Farming | Crop Farming |
| **Technology #1** | Standard Technology | Standard Technology | Farming w/ Irrigation | Reclamation Water |
| **Technology #2** | | ET-Based Irrigation Scheduling | | Oilseed, Grain & Hay Farming |
| **Technology #3** | | Rainwater Harvesting | | Vegetable & Fruit Farming |

### 3.4.1 Residential Build-Up (S1 & S2)

Under Scenarios 1 and 2 (referred to as S1 and S2 in Table 3-1), it is assumed that low-density residential build-up, assumed to equate to 2.82 people/acre, has occurred in the upstream region due to an increase in Fauquier County residents. These new residents are assumed to work either outside of the county or within educational, medical, and other professional services utilized by county residents. As a result of this population increase, the final demand associated with the residential sector and professional services within the economic system under S1 and S2 are assumed to increase to five times the demand associated with these sectors during the base year. The final demand associated with the other economic sectors is assumed to remain the same as 2012 base year conditions. No changes in climate are considered in these scenarios and it is also assumed that no wastewater generated in Fauquier County is being discharged into Cedar Run Watershed. Finally, all new low-density residential and institutional land uses, which correspond with the residential sector and professional services respectively, are assumed to be equally distributed among the seven segments that make up the upstream region.

Only one technology is available to the residential sector under S1 ($t = n$), which is assumed to maintain the same water withdrawal requirements per unit of output for this scenario as in the base year and is referred to as Standard Technology in Table 3-1. Under S2, two alternative technologies are introduced in the residential sector ($t \geq n$). These two alternatives are selected based on the work of Tucker [38]: Evapotranspiration (ET) based Irrigation Scheduling, and Rainwater Harvesting. ET-based Irrigation Scheduling is an alternative technology where only water lost by evapotranspiration is replaced by withdrawn water in residential lawn care [38]. When compared to the factor requirements per unit of output for Standard Technology utilized under S1, the factor requirements for ET-based Irrigation Scheduling are assumed to differ in the following way:

- 35% decrease in water withdrawal requirements per unit of output

Rainwater Harvesting refers to the collection and use of rainwater in and around residencies. It is also assumed to be an expensive system to install and maintain [38]. When compared to the factor requirements per unit of output for Standard Technology utilized under S1, the factor requirements for Rainwater Harvesting are assumed to differ in the following ways:

- 90% decrease in water withdrawal requirements per unit of output
- 60% increase in water price

### 3.4.2 Agricultural Intensification (S3 & S4)

Under Scenario 3 and 4 (referred to as S3 and S4 in Table 3-1), because of an increase in agricultural production for export, the final demand associated with the crop farming sector within the economic system is increased so that all the upstream land available is converted to cropland. Under these scenarios, it is assumed that no additional urban development has occurred, and that the county population has not significantly increased. Any in-migrants are assumed to work in the same sectors as the current labor force and economic output only increases for existing economic sectors. In-migrants who work outside of the county are not considered in these scenarios. Finally, it is also assumed that surface water irrigation is being implemented for new agricultural activity in the crop farming sector so that the amount of water being removed from the watershed under S3 and S4 is about two orders of magnitude higher when compared to base year conditions. It was expected that upstream agricultural intensification would remove more water and generate a higher nitrate concentration in the watershed than upstream residential build-up.

Only one agricultural practice is available to the crop farming sector under S3 ($t = n$), which is assumed to utilize irrigation water requirements per unit output while maintaining the base year requirements per unit of output for the other factors of production. This practice is referred to as Farming with Irrigation in Table 3-1. Under S4, three alternatives are introduced in the crop farming sector ($t \geq n$): Reclamation Water, Oilseed, Grain & Hay Farming, and Vegetable & Fruit Farming. RCOT selects the set of practices that minimizes total factor use while satisfying final demand. Reclamation Water refers to the use of treated wastewater, supplied by the reclamation plant located in another sub-basin of Occoquan Watershed [15], in new agricultural activities in combination with locally withdrawn water. As a result, when compared to the factor requirements per unit of output for Farming with Irrigation utilized under S3, the factor requirements for Reclamation Water differ in the following ways:

- 60% decrease in water withdrawal requirements per unit of output
- 20% decrease in nitrogen requirements per unit of output

Oilseed, Grain & Hay Farming refers to the selection of these crops, such as hay or corn, in new agricultural activities. When compared to the factor requirements per unit of output for Farming with Irrigation utilized under S3, the factor requirements for Oilseed, Grain & Hay Farming differ in the following ways:

- 13% decrease in labor requirements per unit of output
- 31% increase in land requirements per unit of output
- 16% increase in water withdrawal requirements per unit of output

Vegetable & Fruit Farming refers to the selection of these types of crops, such as apples or grapes, in new agricultural activities. When compared to the factor requirements per unit of output for Farming with Irrigation utilized under S3, the factor requirements for Vegetable & Fruit Farming differ in the following ways:

- 40% increase in labor requirements per unit of output
- 92% decrease in land requirements per unit of output
- 48% decrease in water withdrawal requirements per unit of output
- 40% decrease in nitrogen requirements per unit of output

## 3.5 Results

Scenario results include those produced by the factor use ($\varphi$) vector of the economic model (see Table 3-2), which are obtained using a version of the RCOT model programmed using LINGO software [39]. Examples of the output data obtained from RCOT are included in Sections B.1.8, and B.1.9 of Appendix B. Under S1 and S2, when the final demand associated with the residential sector and professional services is expanded to five times the 2012 base year conditions, the number of permanent jobs increase by 180%. The quantity of applied nitrogen increases by 61% because of the expansion of residential land use under S1 and S2. The quantity of withdrawn water increases by 220% under S1, but it only increases by 170% under S2 because RCOT selects ET-based Irrigation Scheduling over the standard technology as the most efficient solution for that scenario.

Under S3 and S4, when the final demand associated with crop farming is expanded from 2012 base year conditions, the number of jobs increases by 7.7% and 12%, respectively.

The quantities of withdrawn water and applied nitrogen increase in S3 by 320% and 240%, respectively. However, under S4, these quantities increase by only 170% and 120%, respectively because RCOT selects a transition to Vegetable & Fruit Farming over an expansion in Oilseed, Grain & Hay Farming as the most efficient solution for that scenario. As a result, while cropland increases by 270% under S3, the cropland reduces by 58% under S4. This information is transferred to HSPF in data tables for land use (Section B.2) and nitrogen deposition (Section B.3), and in time series for water withdrawal (Section B.4).

**Table 3-2.** Percent (%) increase in factor usage relative to 2012 base year

| **Scenario** | **S1** | **S2** | **S3** | **S4** |
|---|---|---|---|---|
| **Jobs** | 180 | 180 | 7.7 | 12 |
| **Water Withdrawn** | 220 | 170 | 320 | 170 |
| **Nitrogen Applied** | 61 | 61 | 240 | 120 |
| **Cropland** | -2.4 | -2.4 | 270 | -58 |

Additional scenario results include output from each downstream segment of Cedar Run Watershed recognized by HSPF, specifically the percent of available surface water that is extracted from each segment of the watershed (see Table 3-3) and the average annual total nitrogen concentration present in the outflow from each of these segments (see Table 3-4). Examples of the output data obtained from HSPF for these scenarios are found in Section B.5 of Appendix B. Because the economic model, RCOT, is coupled with HSPF, the localized environmental impacts caused by an expansion in upstream economic activity can be captured in the different segments of the watershed. When choices are introduced into RCOT, the environmental constraints imposed on the economic system by the watershed system also cause changes in human decisions that alleviate water quantity and quality impacts throughout the watershed segments. As a result of upstream development under S1, 17% of naturally available surface water is removed from Segment 47, which represents the downstream outflow from Cedar Run Watershed. Under S2, 13% of available surface water is removed from Segment 47 because of upstream development. When upstream residential build-up occurs under S1, the average annual nitrogen concentration increases to 2.3 mg/L in Segment 41 because outflow from the upstream region flows into the downstream region through this segment. Similarly, under S2, the average annual nitrogen concentration increases to 2.2 mg/L in Segment 41 because of upstream development. The concentration of nitrogen in Segment 47 increases to 1.8 mg/L because of upstream development under S1 and S2.

**Table 3-3.** Percent (%) of available surface water removed annually

| | Segment | S1 | S2 | S3 | S4 |
|---|---|---|---|---|---|
| **Downstream** | 41 | 24 | 19 | 35 | 19 |
| | 42 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 43 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 44 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 47 | 17 | 13 | 25 | 12 |

When upstream agricultural intensification occurs under S3, the average annual nitrogen concentration increases to 6.5 mg/L in Segment 41 because of upstream agricultural intensification. Under S4, the average annual nitrogen concentration increases to 2.9 mg/L in Segment 41. As a result of upstream development under S3, 25% of naturally available surface water is removed from Segment 47, which represents the downstream outflow from Cedar Run Watershed. Under S4, 12% of available surface water is removed from Segment 47 because of upstream development. The concentration of nitrogen in Segment 47 increases to 4.2 mg/L because of upstream development under S3, but only increases to 2.0 mg/L under S4. As indicated by S3, upstream agricultural intensification removes more water and generates a higher nitrate concentration in the watershed than an upstream residential build-up with a human density of 2.82 people/acre, which was expected. S4 indicates that choices in crop allowed upstream agricultural intensification to utilize less water and nitrogen while still meeting the final demand associated with crop farming, unexpectedly making this development pattern competitive with residential development from an environmental standpoint.

**Table 3-4.** Average annual total nitrogen concentration in outflow from downstream segments (mg/L)

| | Segment | Baseline | S1 | S2 | S3 | S4 |
|---|---|---|---|---|---|---|
| **Downstream** | 41 | 0.6 | 2.3 | 2.2 | 6.5 | 2.9 |
| | 42 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| | 43 | 0.5 | 0.6 | 0.6 | 0.6 | 0.5 |
| | 44 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| | 47 | 0.6 | 1.8 | 1.8 | 4.2 | 2.0 |

### 3.6 Discussion

The results for S1 and S2 demonstrate how the downstream impacts on watershed health caused by upstream residential build-up can be alleviated through changes in technology. When ET-based Irrigation Scheduling and Rainwater Harvesting are introduced as alternative technologies within the residential sector under S2, ET-based Irrigation Scheduling is selected as the most efficient solution to satisfy the objective functions within RCOT. While Rainwater Harvesting reduces water requirements significantly more than ET-based Irrigation Scheduling, the increase in factor price associated with that technology makes it sub-optimal from an economic standpoint. This selection under S2 reduces the amount of water lost downstream in Cedar Run Watershed, represented by the outflow from Segment 47, by 4% when compared to the results of S1. When compared to the results of S1, no changes in the elevated nitrogen concentration result from the alternative technologies that are introduced under S2. Under both S1 and S2, the nitrogen concentration is only elevated to 1.8 mg/L in downstream outflow, which is much less than the nitrogen limits specified for Occoquan Reservoir by regional policy. Thus, this sub-basin would have a minimal impact on water quality further downstream. The limited elevation in downstream nitrogen concentration could have resulted from wastewater being discharged into another sub-basin of Occoquan Watershed as indicated by the locations of wastewater treatment plants on the map of facilities available on the Fauquier County Water and Sanitation Authority website.

The results for S3 and S4 demonstrate how the downstream effects of upstream agricultural intensification can be alleviated through strategic crop selection. When choice in crop is introduced into the crop farming sector under S4, fruits and vegetables are selected over oilseed and grain production as the most efficient solution to satisfy objective functions because fruit and vegetables require less resources than oilseed and grains to produce the same unit of economic output. This selection of crops under S4 reduces the amount of cropland required to achieve final demand by 58%, which also reduces the quantities of water and nitrogen utilized by the crop farming sector. As a result, there are significant reductions in the quantity of water removed and in the nitrogen concentration when compared to the results of S3. These results align with current local trends in agricultural activity within Fauquier County where traditional farming operations are being replaced by small produce and specialty farming operations, such as vineyards, which can be run successfully on small parcels of land with five acres being a common size [14]. This shift from cereals to other more high-value crops is also observed in a scenario analysis conducted by Springer and Duchin [40] using RCOT, which examines shifts in agricultural activity at the global scale in response to projected global populations.

New economic activity can have varying impacts on watershed health depending on the spatial location of the new activity and depending on human decisions made within the sectors of the economy. These effects also accumulate to impact water loss and nitrogen concentration further downstream. The localized environmental impacts and downstream effects on the watershed cannot be obtained from RCOT alone because I-O models are spatially lumped as are other types of economic models, such as the computable general equilibrium model [9, 41]. However, RCOT's unique features allow for technology options for all economic sectors and minimize resource use based on constraints in resource availability imposed by the watershed, which captures human decisions that are based on the physical reality of a region [17]. By coupling RCOT, with a spatially distributed watershed model, HSPF, the interactions between the economic and watershed systems are captured at a higher level of spatial detail than purely administrative boundaries or watershed criteria. Thus, this coupled hydrologic-economic modeling framework has the capacity to overcome the spatial differences of the individual models and the types of questions one can address are substantially expanded beyond those that can be analyzed using these models separately. Nevertheless, the interdependency of regions is important to consider when addressing local questions so a multi-regional analysis that spans multiple watersheds may reveal additional information about the impacts of future residential development that could occur in Fauquier County. It is also important to acknowledge the uncertainty that is inherent in the individual models, such as the uncertainty associated with assumptions and with the causal relationships between variables [42]. When coupling these models, the uncertainties might be compounded, but it is also possible that some uncertainty will be removed because assumptions are better informed. In these initial studies, the framework serves its intended purpose and methods to address this uncertainty can be undertaken in the future.

### 3.6.1 Conclusions

In the case of upstream residential build-up in Cedar Run Watershed, an alternative technology is more efficient than the standard technology for providing water for upstream residents while ensuring an adequate water supply in the downstream location. When upstream changes take the form of an increase in agricultural activities, a shift in crops from grains to fruits and vegetables, which are higher-value crops, is the most efficient of the alternatives considered. Thus, the most efficient solution is the one that minimizes the use of resource inputs, including developed land, surface water withdrawn, and nitrogen applied as fertilizer, which in turn inform downstream watershed health. It is important for spatially resolved input-output and hydrological data to be collected because it enables this systems research applied to a variety of watersheds in other physical and societal contexts. If the data are available from third-party institutions or academic researchers, then this coupled modeling framework can capture the interactions between the economic and watershed systems in empirical studies applied at any level of spatial resolution, including the sub-county and sub-basin scales.

### 3.6.2 Future Work

The coupled hydrologic-economic modeling framework will be applied in other locations with compelling environmental concerns and economic sectors that are different from those present in Fauquier County. Full-scale empirical studies using the WTM/RCOT model, developed in [43], linked with a watershed model, such as HSPF, would make it possible to study a region, such as Chesapeake Bay Watershed, by representing the ensemble of sub-watershed economic regions and the economic relations among them, linked with a model of the entire watershed with the necessary spatial disaggregation.

Social systems may also be incorporated into the hydrologic-economic modeling framework for future studies because this modular framework is suitable for a system-of-systems approach that integrates different models from different knowledge domains to better represent a socio-environmental system that can be used to inform decisions [44-46].

### 3.7 Acknowledgments

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# Chapter 4 Applying a coupled hydrologic-economic modeling framework: Evaluating conjunctive use strategies for alleviating seasonal watershed impacts caused by agricultural intensification

Maria Amaya[1], Faye Duchin[2], Erich Hester[1], John C. Little[1]

[1]Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, Virginia, USA

[2]Department of Economics, Rensselaer Polytechnic Institute, Troy, New York, USA

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## 4.1 Abstract

Economic models and watershed models provide useful results, but when seeking to integrate these systems, the temporal units typically utilized by these models must be reconciled. A hydrologic-economic modeling framework is built to couple the Hydrological Simulation Program-Fortran (HSPF), representing the watershed system, with the Rectangular Choice-of-Technology (RCOT) model, an extension of the basic input-output (I-O) model. This framework is implemented at different sub-annual timesteps to gain insight in selecting temporal units best suited for addressing questions of interest to both economists and hydrologists. Illustrative scenarios are designed to examine seasonal increases in nitrogen concentration that occur because of agricultural intensification in Cedar Run Watershed, located in Fauquier County, northern Virginia. These scenarios also evaluate the selection among surface water, groundwater, or a mix of (conjunctive use) practices for irrigation within the crop farming sector in response to these seasonal impacts. When agricultural intensification occurs in Cedar Run Watershed, implementing conjunctive use in irrigation reduces the seasonal increases in nitrogen concentration to specified limits. The most efficient of the conjunctive use strategies explicitly considered varies depending on which timestep is utilized in the scenario: a bi-annual timestep (wet and dry season) versus a seasonal timestep. This modeling framework captures the interactions between watershed and economic systems at a temporal resolution that expands the range of questions one can address beyond those that can be analyzed using the individual models linked in this framework.

**Keywords:** modeling, framework, economic, hydrologic, watershed, temporal

## 4.2 Introduction

Throughout the 19th and 20th centuries, economic concepts have been applied in water engineering to gain insight into assessing water management concerns across different scales, such as forecasting water demand, negotiating water policy, and evaluating engineering designs (Lund, Cai, & Characklis, 2006). Water also serves as a resource used in both production and consumption, as well as a sink for the pollution byproducts of this economic activity. Thus, while water is utilized within economic systems, the impact of economic use on water quantity and quality must be considered as well (Brouwer & Hofkes, 2008).

Beginning in the 1960s and 1970s, hydro-economic modeling has been developed by hydrologists and engineers to represent the hydrologic and economic aspects of a region within a framework (Harou et al., 2009). However, when trying to integrate these hydrologic and economic systems, several challenges have arisen. First, when establishing relationships between variables, economic models often use statistical inference while watershed models are typically based on empirical relationships (Brouwer & Hofkes, 2008; McKitrick, 1998). Second, watershed models are usually spatially defined at the basin scale and economic models are defined by administrative boundaries. Third, watershed models are defined at fine temporal scales, such as hours or days, while economic models are temporally defined at the annual scale (Brouwer & Hofkes, 2008). A modular hydrologic-economic modeling framework was designed by Amaya, Baran, Lopez-Morales, and Little (2021) to reconcile these differences. The first challenge is addressed by the coupling of a physically constrained, I-O model, representing the economic system, with a deterministic, physically based watershed model. The second challenge is the focus of another study while the third challenge is the focus of this paper.

### 4.2.1 Sub-annual Temporal Analysis

Leontief (1970) extended the economic input-output (I-O) model to include an environmental database to evaluate the pollution generated by economic consumption and production. Since their conception, environmentally extended, input-output (EEIO) databases have been used throughout the world to examine water use, waste generation, land use, and other environmental impacts resulting from economic activity. An average annual temporal resolution is commonly used in these EEIO applications since available I-O databases are typically aggregated to that scale (Sun, Tukker, & Behrens, 2019). Long-term EEIO analyses have also been conducted for multi-year time periods, such as an assessment of net energy consumption in Australia over a period of ten years (He, Reynolds, Li, & Boland, 2019) and an I-O analysis of carbon emissions from an urban region in China was also examined for a 10-year time period (Wang, Zhan, Li, Zhang, & Zhang, 2019). The temporal aggregation of annual I-O tables can be misleading because it overlooks any seasonality that occurs in production throughout the year and cannot accurately evaluate unexpected events, whether natural or man-made, that generate impacts within time periods shorter than the annual scale (Avelino, 2017; Donaghy, Balta-Ozkan, & Hewings, 2007). A sub-annual temporal scale is important to consider to accurately estimate the environmental impacts of economic activity. However, according to Avelino (2018), the temporal disaggregation of I-O tables has had limited attention.

Temporally disaggregated I-O tables can capture the seasonal production patterns within different economic sectors, such as the agricultural sector. This seasonality in agricultural activity could also result in the time-varying distribution of resources, such as water or fertilizer, throughout the year. Temporally disaggregated, environmentally extended, I-O databases could improve accuracy when incorporating environmental processes and pollution patterns into the I-O model, which operate at sub-annual time intervals (Avelino, 2017, 2018). With the possibility of linkage with a watershed model, there is also an opportunity for the sub-annual temporal analysis of water withdrawal and discharge to become more feasible within EEIO analysis (Sun et al., 2019). Thus, utilizing the hydrologic-economic modeling framework described by Amaya et al. (2021) can improve the ability to choose temporal units for the economic model that are best suited to integrating the watershed model when addressing specific kinds of questions.

### 4.2.2 Conjunctive Use

In many places around the globe, surface water has interactions with groundwater, which indicates that the utilization of one resource will impact the availability of the other. Surface water and groundwater have traditionally been managed as separate entities, but the potential of conjunctive water use and management has begun to be more closely examined as a solution to issues of water quantity and quality (Cobourn, Elbakidze, & Ghosh, 2017). While multiple definitions of conjunctive use are available in the literature, the definition that will be used in this paper, originally defined by the Food and Agriculture Organization of the United Nations in 1995, refers to conjunctive use as "harmoniously combining the use of [surface water and groundwater] in order to minimize the undesirable physical, environmental, and economical effects of each solution" (California Natural Resources Agency, 2016). When there is not enough surface water available for utilization, groundwater extractions tend to increase, which could lead to aquifer depletion. Conjunctive use could offer the alternative of storing surface water underground for future use when it is not practical to build storage dams (Bouwer, 2002). Mixing different sources of water could also improve water quality through blending (Ross, 2017). However, coherent water management must be clearly established to successfully implement conjunctive use policies. There must also be an adequate surplus of surface water available within a basin to exchange for groundwater. The coordination and infrastructure required to obtain, transport, and store different sources of water could also result in higher costs associated with these conjunctive use policies (Blomquist, Heikkila, & Schlager, 2001).

One of the largest consumers of water resources is irrigated agriculture, but this utilization is threatened by water scarcity in arid regions and excessive amounts of water for irregular time periods in coastal regions (Rao, Bhallamudi, Thandaveswara, & Mishra, 2004; A. Singh, 2014). Studies have been conducted on the implementation of conjunctive use for irrigated agricultural activity in these different types of regions, such as in a semi-arid region of Iran with a high level of irrigated agriculture (Montazar, Riazi, & Behbahani, 2010) or in the east coastal deltas of India where there is intense rice cultivation (Rao et al., 2004). In these studies, conjunctive use of surface water and groundwater was determined to be a plausible solution to optimize availability and stability of these water resources for agricultural use throughout the wet and dry periods of the year. Because there are multiple aspects that determine if conjunctive use will be successful when implemented within a region, a modeling approach is useful to evaluate and determine the most effective conjunctive use strategy for a specific region as was done by Khan, Voss, Yu, and Michael (2014). Utilizing a modeling framework that considers both the hydrologic and economic aspects of a region is also useful when assessing conjunctive use strategies. For example, Pulido-Velazquez, Andreu, and Sahuquillo (2006) developed an optimization model to determine the maximum economic benefit resulting from various conjunctive management policies in Spain. Water allocation is determined using a demand curve to calculate the economic value within the study region. The modeling framework developed by Amaya et al. (2021) also utilizes an economic optimization model, but as an I-O model, it can provide sectoral detail for an entire regional economy and calculate physical quantities of resources, including water, used to meet final demand associated with each sector. Thus, additional complexity is added to the representation of the economic system and its interactions with the watershed in the coupled framework (Amaya et al., 2021).

### 4.2.3 Region of Study

This paper examines agricultural expansion within a regional economy, its seasonal impacts on water quality that occur within the local watershed, and the selection among conjunctive use strategies within the economic system in response to these impacts. The area of study is Fauquier County, which is in northern Virginia in the United States. This county has a long history of agricultural activity with approximately 54% of the county land area currently being used as farmland. Due to its proximity to the Washington DC metropolitan area, Fauquier County has also been experiencing urban development pressure. County officials are interested in preserving the rural aesthetic of the county and supporting the agricultural sector of its economy. These interests are currently being addressed by zoning 90% of the county for agricultural use (Rephann, 2015; Fauquier County Board of Supervisors, 2019).

Within Fauquier County lies Cedar Run Watershed (498 $km^2$), which is a sub-basin of Occoquan Watershed (1,515 $km^2$) located 50 km southwest of Washington DC. Because algal blooms were once frequent in the Occoquan Watershed, nitrogen enrichment and eutrophication are considered primary water quality concerns for the region. As a result, both water quality and flow volume have been measured continuously within this watershed by the Occoquan Watershed Monitoring Laboratory (OWML) since 1973 (Xu, Godrej, & Grizzard, 2007). The Occoquan Policy was also established to regulate water quality within the Occoquan Reservoir, which is the drainage point for the Occoquan

Watershed. Following this policy, the ambient nitrate concentration must not exceed 5.0 mg/L in the reservoir, otherwise nitrogen removal facilities must be activated (State Water Control Board, 2020). Thus, elevated nitrogen concentrations and increased water withdrawal caused by agricultural intensification within Cedar Run Watershed need to be carefully evaluated and utilizing a seasonal timestep within the economic system may allow for a more precise analysis.

### 4.2.4 Research Objectives

Several scenarios involving agricultural expansion and irrigation within Fauquier County are evaluated along with the seasonal increases in nitrogen concentration that occur within Cedar Run Watershed because of the new agricultural activity. The influence of these seasonal impacts on selections made among different conjunctive use strategies available within the crop farming sector of the economy are also examined. The modular hydrologic-economic modeling framework conceptualized by Amaya et al. (2021) is utilized to conduct this analysis and to demonstrate that it can capture the interactions between economic and watershed systems at sub-annual temporal scales, which expands the range of questions that can be addressed using the models linked in this framework.

A physically constrained, I-O model, RCOT, is used to represent the economic system in this modeling framework. This model can represent the entire economy of Fauquier County as distinct economic sectors and can represent the economy in terms of physical phenomena, such as the material flow of goods, rather than just monetary values, which allows for straightforward exchange of information between the watershed and economic systems. RCOT also has the unique feature of endogenously selecting among choices introduced within the economic sectors to maximize efficiency by constraining factor use to not exceed policy constraints or available endowment (Duchin & Levine, 2011). Choices in source and application of irrigation water can be introduced in the crop farming sector of the economy and then selected within the economic model based on factor price and environmental constraints. In these scenarios, the annual I-O tables utilized by RCOT are temporally disaggregated to both the bi-annual and seasonal timesteps to capture the seasonality of the environmental impacts of agricultural intensification within Cedar Run Watershed.

HSPF is used to represent the watershed system within the modeling framework. This model has already been calibrated to represent the hydrologic processes of Cedar Run Watershed by OWML using local weather data collected from 2008 to 2010, such as regional cloud cover, wind speed, air temperature, dew point temperature, and precipitation, and has been validated using data collected from 2011 to 2012 (Bartlett, 2013; Xu, 2005). Once the model is run for this 5-year simulation period, nitrogen loading, and water flow volumes are output at the daily timestep and can be summed to larger timesteps. Using the Irrigation Module of HSPF, the source of irrigation water can be specified as groundwater, surface water, or a source external to the watershed. This module is also used to specify if the irrigation water is applied to the soil surface, lower soil layer, or directly into the active groundwater table. Thus, by linking an I-O model, RCOT, with a continuous watershed model, HSPF, the seasonal impacts of new agricultural activity on water quality can be examined at a sub-annual temporal resolution along with how these impacts inform choices made among irrigation strategies available within the agricultural sector of the economy. In summary, the following questions will be addressed in this paper:

1. Can the introduction of conjunctive use alleviate the seasonal impacts on water quantity and nitrogen concentration caused by agricultural intensification and irrigation within Cedar Run Watershed?
2. Does a 3-month timestep produce different output results from this coupled hydrologic-economic modeling framework than when a 6-month timestep is used?
3. Does coupling a physically constrained, I-O model with a continuous watershed model provide two-way feedback that captures the interactions between the economic and watershed systems at a temporal resolution that expands the types of questions that may be addressed by either of the models coupled in this framework?

## 4.3 Methodology

### 4.3.1 HSPF

HSPF is a deterministic, lumped parameter, physically based model designed to continuously simulate the water quantity and quality processes that occur within a watershed at the daily timestep. In this model, the watershed system is presented as a set of constituents, such as water and pollutants, that move through a fixed environment as they interact with each other. The watershed is subdivided into elements composed of zones and nodes. Zones refer to discrete sections of the environment that may be associated with the integral of a spatially variable quantity. Nodes are defined as points in space that may be associated with a specific value of a spatially variable function and can be used to define the boundaries of zones. Thus, the relationship between zones and nodes can be described as the relationship between a function's definite integral and the values at the limits of integration. Bicknell, Imhoff, Kittle, Jobes, and Donigian (2001) provide more detail on the processes and all the parameters utilized in HSPF.

There are two types of elements utilized by HSPF: land segments and channel reaches. Elements classified as the same type embody the same nodal arrangement and utilize the same group of parameters. Land segments are defined as areas of land with similar hydrologic characteristics. These elements do not have any nodes and are represented as layered zones in which constituents may accumulate: the soil surface layer, subsurface soil layers, and the groundwater table (see Figure 4-1). These constituents, such as water and nitrogen, move from one land segment downslope to another segment or channel reach. Channel reaches are one-dimensional elements represented by a single zone located between two nodes. Parameters, including flow rate and depth, are modeled at these nodes while the zones correspond with storage values that receive inflows and disperse outflows.

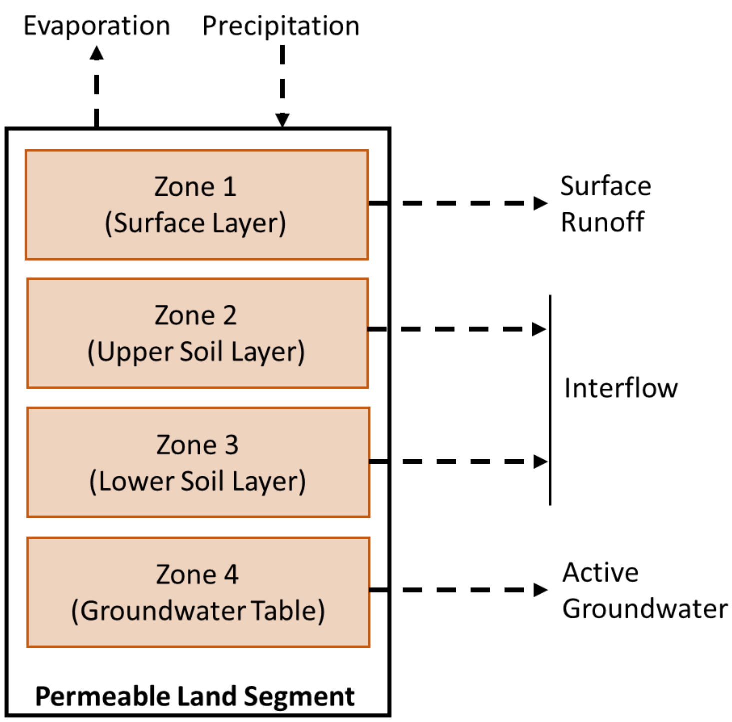


**Figure 4-1.** The zones that compose the element type, Permeable Land Segment, and the movement of the constituent (water) through the zones

HSPF utilizes application modules to support the modeling of water quantity and quality processes that occur within the different elements. The module PERLND models the permeable land segments while RCHRES models the channel reaches. Each of these modules contain sub-modules that model the processes that occur within the corresponding elements. Within PERLND, water quantity processes are modeled using the PWATER sub-module, which models the water flow from each pervious land segment using a water budget equation to predict total runoff from pervious surfaces. The Irrigation sub-module, an addition to the PWATER sub-module, specifies source and application location of irrigation water while utilizing irrigation demand data that has been input into HSPF as an exogenously defined time series. Irrigation water may be extracted from the groundwater or channel reaches before being added to the water budget associated with each permeable land segment using the following equation where irrigation and precipitation are exogenously defined (Bicknell et al., 2001):

$$\frac{d}{dt}V = (\mathbf{P} + \mathbf{Ir}) - \mathbf{E} - \mathbf{G} - \Delta\mathbf{S} \tag{4.1}$$

where,

V = volume of runoff from permeable land segment, P = precipitation, Ir = irrigation, E = evapotranspiration, G = inactive groundwater, ΔS = change in soil storage

PQUAL, another sub-module of PERLND, is used to capture the movement and fate of water quality constituents, such as nitrogen and phosphorus, from the soil of pervious surfaces to the reaches. The deposition and flow of nitrogen through the soil of permeable land segments can be represented by the following mass balance equation where nitrogen deposition is exogenously defined (Bicknell et al., 2001):

$$\frac{d}{dt}N = \mathbf{N_{in}} - \mathbf{D} - [\mathbf{N_{OL}} + \mathbf{N_{SED}} + \mathbf{N_{I}} + \mathbf{N_{GW}}] \tag{4.2}$$

where,

N = nitrogen stored in the soil of permeable land area, $N_{in}$ = nitrogen deposition, D = nitrogen removed by decay, $N_{OL}$ = nitrogen removed by overland flow, $N_{SED}$ = nitrogen removed by detached sediment, $N_{I}$ = nitrogen removed by interflow, $N_{GW}$ = nitrogen removed by active groundwater

HSPF also has utility modules that link the application modules and manage data. These modules utilize data that are input as time series into HSPF, such as precipitation and air temperature, to generate additional time series as output. HSPF also uses the SCHEMATIC module to exogenously specify each land segment's size and composition (Bicknell et al., 2001). The segments of Cedar Run Watershed, recognized in the HSPF model calibrated by OWML, are displayed in Figure 4-2.

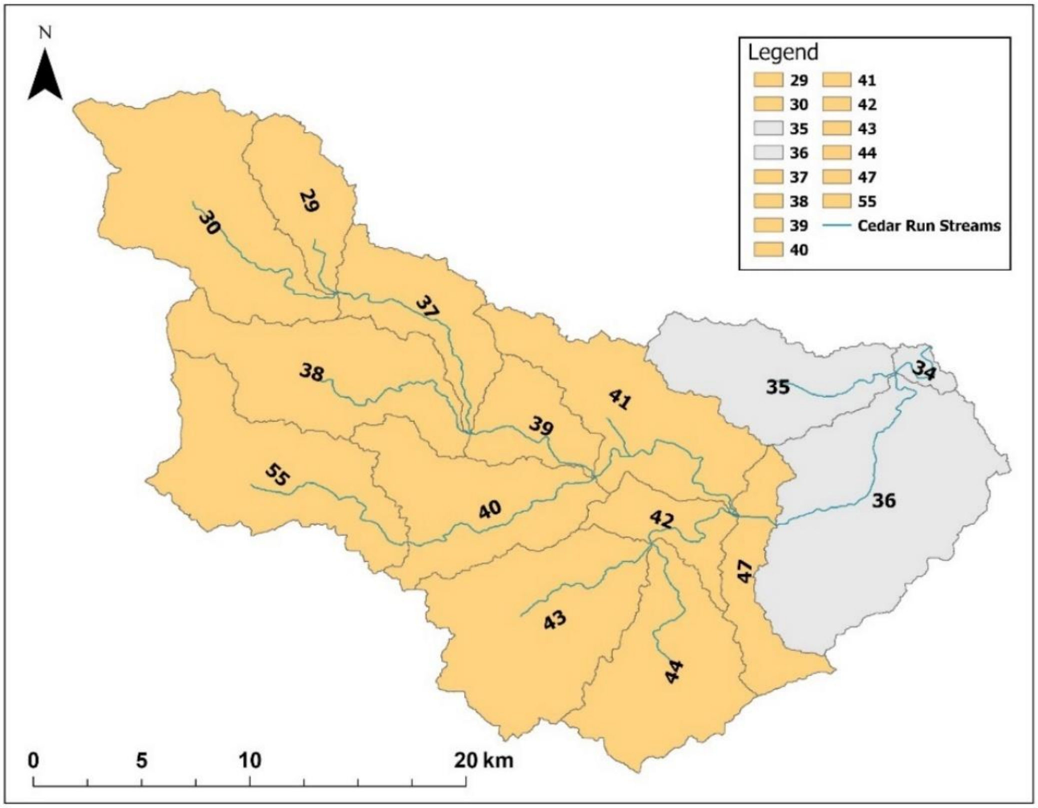


**Figure 4-2.** Cedar Run Watershed divided into numbered segments, including those that lie within Fauquier County (gold) and those that lie outside (gray), with outflow from Segment 47 representing the outflow of the entire watershed within the county

### 4.3.2 RCOT

As an extension of the basic I-O model, RCOT contains two components: the primal quantity model and the dual price model. The primal model calculates economic output and factor use for an economy utilizing *n* industrial sectors and *k* factors of production in physical, monetary, or mixed units (Duchin & Levine, 2011). Factors of production are defined as required inputs that are not produced themselves, including labor, capital, and land. Other resources have also been incorporated into previous I-O applications as factors of production, such as water (Lopez-Morales, 2010) and nitrogen (S. Singh, Compton, Hawkins, Sobota, & Cooter, 2017). Each sector of the economy has corresponding factor requirements needed to produce one unit of output. In the primal model, the basic I-O model utilizes invertible, square matrices defined by the *n* economic sectors, which is a feature of the EEIO sub-field as well. Uniquely, RCOT is a linear program that can select among choices in operational technologies so that specific factor constraints are satisfied. The primal model of RCOT recognizes *t* technologies available to the *n* sectors where $t \geq n$. Parameters and variables, distinguished among both sectors and technologies in vectors and matrices, are denoted by an asterisk in the following equations. Thus, the matrices utilized by RCOT are rectangular rather than square. The logic utilized by RCOT is described in more detail by Duchin and Levine (2011). The following equations are used by the primal model:

$$(\mathrm{I}^* - \mathrm{A}^*)\mathrm{x}^* = \mathrm{y} \rightarrow \mathbf{x}^* = (\mathbf{I}^* - \mathbf{A}^*)^{-1}\mathbf{y} \tag{4.3}$$

$$\phi = \mathrm{F}^*\mathrm{x}^* \rightarrow \phi = \mathbf{F}^*(\mathbf{I}^* - \mathbf{A}^*)^{-1}\mathbf{y} \tag{4.4}$$

where,

$\mathrm{A}^*$ = coefficient matrix $(\mathrm{n} \times \mathrm{t})$, $\mathrm{F}^*$ = matrix of factor requirements per unit of output $(\mathrm{k} \times \mathrm{t})$, y = final demand vector $(\mathrm{n} \times 1)$, $\mathrm{x}^*$ = economic output vector $(\mathrm{t} \times 1)$, $\mathrm{I}^*$ = identity matrix $(\mathrm{n} \times \mathrm{t})$, $\phi$ = factor use vector $(\mathrm{k} \times 1)$

The primal model utilizes an objective function to minimize factor use while maintaining that factor use does not exceed availability and production still satisfies final demand. If the required resource endowments are unable to meet the specified consumer demand, then no feasible solution would result for a scenario. The objective function utilized by the primal model is as follows:

$$\text{Minimize } \boldsymbol{M} = \boldsymbol{\pi}'\mathbf{F}^*\mathbf{x}^* \tag{4.5}$$

$$\text{such that } (\mathbf{I}^* - \mathbf{A}^*)\mathbf{x}^* \geq \mathbf{y} \text{ and } \mathbf{F}^*\mathbf{x}^* \leq \mathbf{f}$$

where,

$\mathrm{x}^*$ = economic output vector $(\mathrm{t} \times 1)$, y = final demand vector $(\mathrm{n} \times 1)$, $\mathrm{A}^*$ = coefficient matrix $(\mathrm{n} \times \mathrm{t})$, f = factor endowments vector $(\mathrm{k} \times 1)$, $\mathrm{F}^*$ = matrix of factor requirements per unit of output $(\mathrm{k} \times \mathrm{t})$, $\pi$ = vector of factor prices $(\mathrm{k} \times 1)$

The dual price model in RCOT calculates the unit cost associated with each economic sector, based on the prices associated with each factor of production, using the following equation:

$$\mathbf{p} = (\mathbf{I}^* - \mathbf{A}^{*\prime})^{-1}\mathbf{F}^{*\prime}\boldsymbol{\pi} \tag{4.6}$$

where,

$\pi$ = vector of factor prices ($k \times 1$), p = sectoral price vector ($n \times 1$), $A^{*\prime}$ = transpose of matrix $A^*$, $F^{*\prime}$ = transpose of matrix $F^*$

The dual price model of RCOT utilizes the following objective function to maximize the money value of final demand minus scarcity rents on fully utilized factors of production:

$$\text{Maximize } \boldsymbol{W} = \mathbf{p}'\mathbf{y} - \mathbf{r}'\mathbf{f} \tag{4.7}$$

$$\text{such that } (\mathbf{I}^* - \mathbf{A}^*)'\mathbf{p} \leq \mathbf{F}^{*\prime}(\boldsymbol{\pi} + \mathbf{r})$$

where,

y = final demand vector ($n \times 1$), $A^*$ = coefficient matrix ($n \times t$), $I^*$ = identity matrix ($n \times t$), f = factor endowments vector ($k \times 1$), $F^*$ = matrix of factor requirements per unit of output ($k \times t$), p = sectoral prices vector ($n \times 1$), r = factor scarcity rents vector ($k \times 1$)

The two objective functions displayed in Equations 4.5 and 4.7 are equal at the optimal solution. This equivalence means that the total cost is equal to the sum of factor costs plus any scarcity rents. A change in the availability or unit price of a resource may result in a change in the choice selection among the technologies available to the different sectors of the economy (Duchin & Levine, 2011).

### 4.3.3 Building the Economic Database

OWML has already calibrated an HSPF model to represent Cedar Run Watershed using local monitoring data collected from 2008 and 2012, but an economic database representative of Fauquier County had to be constructed for RCOT. To construct this database, sectoral economic data are obtained for the county representative of year 2012. This year serves as the base year because the most complete database that could be assembled for Fauquier County is representative of 2012. County-level, monetary, input-output data, and industry final demand data based on government data are obtained from a private company called IMPLAN Group, LLC (2016). IMPLAN obtains data from different sources and provides estimates for unavailable data, which are gauged against other data to ensure accuracy, to compile their I-O datasets.

Following the guidelines provided by Miller and Blair (2009), the I-O data obtained from IMPLAN are aggregated into seven basic industrial sectors: agriculture, mining, construction, manufacturing, utilities, professional services, and government services. These sectors are aggregated using the North American Industry Classification System (NAICS), which is recognized by the United States Census Bureau (2017). For more detailed analysis of agricultural activity, the agriculture sector is then disaggregated into three sectors as was done by Julia and Duchin (2007): crop farming, animal husbandry, and other agricultural activities. Once this data is input into RCOT, the model is run to calculate the economic output associated with each industrial sector for the 2012 base year. These output results are then assessed to ensure that the model reproduces the economic output data obtained from IMPLAN Group and to verify that this model is an accurate representation of the Fauquier County economy. Thus, Fauquier County is represented as an economic system composed of nine industrial sectors in RCOT.

To build the factor requirement ($F^*$) matrix for RCOT, six factors of production are identified: labor, capital, land, water withdrawn, nitrogen applied as fertilizer produced outside of Fauquier County, and nitrogen applied as manure generated by the livestock associated with animal husbandry. Annual labor and capital requirements for each economic sector are calculated using sectoral data for labor, capital, and economic output obtained from IMPLAN. Sectoral land requirements are determined based on land cover data obtained from the Virginia Geographic Information Network (2016) and zoning data provided by the Fauquier County GIS Office (2014). Water withdrawal requirements for each industrial sector are determined using county water data provided by the United States Geological Survey (2010) and data obtained from an I-O database compiled by the Green Design Institute at Carnegie Mellon University (Blackhurst, Hendrickson, & Vidal, 2010). Agricultural nitrogen requirements are assumed based on data available for Fauquier County from the National Agricultural Statistics Service (NASS). In the scenarios where conjunctive use is introduced, excess nitrogen loading is included as a seventh factor of production to distinguish between the nine irrigation strategies that are introduced. Excess nitrogen loading is defined as the increase in nitrogen loading resulting from an increase in runoff caused by the addition of irrigation water. The quantity of excess nitrogen associated with each irrigation practice is determined by running HSPF under the different irrigation configurations and incorporating this information into RCOT.

The economic database constructed to represent Fauquier County is built using data available at the annual time scale. To run the economic model at the sub-annual time scale, the final demand (y) vector and the factor requirement ($F^*$) matrix had to be adjusted for each sub-annual timestep. HSPF begins its simulation on January 1st, 2008 and ends on December 31st, 2012. Regional cloud cover, wind speed, air temperature, and dew point temperature collected at the weather station at Washington Dulles International Airport during this 5-year period are included as input into the model at the daily timestep along with precipitation data collected at the rain gauge station located in Cedar Run Watershed. Solar radiation and potential evapotranspiration data were also input into the model during the calibration process (Bartlett, 2013; Xu, 2005). Thus, HSPF models the climate patterns that occur in Cedar Run Watershed throughout the year and their influence on the watershed. Assuming the meteorological data collected between 2008 and 2012 are typical of the study region, average watershed outflow is higher during the first six months of a year (January through June) than during the second six months (July through December). Thus, in scenarios where a 6-month timestep is used, the first timestep is referred to as the wet season and the second timestep is referred to as the dry season. In scenarios where a 3-month timestep is used, the first timestep refers to January through March (Winter), the second timestep refers to April through June (Spring), the third timestep refers to July through September (Summer), and the fourth timestep refers to October through December (Fall). The seasons are assumed to correspond with these 3-month timesteps. There is about a 10-day lag between the beginning of a season and the beginning of a month, but these approximations are reasonable for the scenarios being evaluated.

Because winter wheat and barley are listed as field crops in Fauquier County by NASS and in the report assembled by Rephann (2015), it is assumed that seasonal crop rotation is being practiced within the crop farming sector. As a result, when a 6-month timestep is used, it is assumed that the annual final demand associated with each economic sector is equally distributed among the wet and dry seasons of a year as shown in Table 4-1. 20% of the water annually required for agricultural activity is withdrawn during the wet season and the remaining 80% is withdrawn during the dry season to compensate for high evapotranspiration rates and lower channel outflow. It is assumed that the fertilizer required for the crop farming sector is applied during the wet season while fertilizer required for animal husbandry is applied during the dry season. When a 3-month timestep is used, it is assumed that the annual final demand associated with each economic sector is equally distributed among the four seasons in a year. This assumption may be a simplification but serves for the demonstrative purposes of this study. It is assumed that 10% of the water annually required for agricultural activity is withdrawn during Winter, Spring, and Fall while the remaining 70% is withdrawn during Summer because average channel outflow is lowest during this season. It is also assumed that fertilizer required for crop farming is applied during Winter and that fertilizer required for animal husbandry is applied during Summer. Annual labor and land requirements are assumed to be constant throughout the seasons that make up the year.

**Table 4-1.** Percent (%) of annual final demand and factor requirements utilized in each season

| | **6-Month Timestep** | | **3-Month Timestep** | | | |
|---|---|---|---|---|---|---|
| **Timestep** | **Wet** | **Dry** | **Winter** | **Spring** | **Summer** | **Fall** |
| Annual Final Demand | 50% | 50% | 25% | 25% | 25% | 25% |
| Annual Water Required (Crop Farming) | 20% | 80% | 10% | 10% | 70% | 10% |
| Annual Fertilizer Required (Crop Farming) | 100% | 0% | 100% | 0% | 0% | 0% |
| Annual Fertilizer Required (Animal Husbandry) | 0% | 100% | 0% | 0% | 100% | 0% |
| Annual Land Required | 100% | | 100% | | | |
| Annual Labor Required | 100% | | 100% | | | |

### 4.3.4 Coupled Modular Framework

The coupled modeling framework being utilized is described by Amaya et al. (2021), but it will also be described in this sub-section and is visually presented in Figure 4-3. To manage the different scenarios being evaluated, HSPF is run using URUNME, which is an integrated modeling software application that has recently been developed. This software is utilized as a user interface to help facilitate the exchange of information between the two models (Lodhi, Godrej, Sen, Angelotti, & Brooks, 2019; Lodhi, Godrej, Sen, & Baran, 2020). To begin, HSPF is run under baseline conditions, which assumes no changes in the meteorological and land use characteristics that were calibrated for Cedar Run Watershed using the data measured from 2008 to 2012, before summing the resulting watershed outflow and nitrogen loading to the first timestep (either 6-month or 3-month). This information is then used to determine the available quantities of factors of production in the f vector of RCOT, specifically land, water, and nitrogen. The final demand for the crop farming sector is adjusted in the y vector for the scenario being evaluated and then the economic model is run. The resulting output from RCOT includes economic output from the x vector, price per economic sector from the p vector, and the quantities of factors used to meet final demand from the ϕ vector. Information from the ϕ vector is then transferred to HSPF. Specifically, land use composition and nitrogen deposition ($N_{in}$) are exogenously adjusted within the SCHEMATIC and PQUAL modules of HSPF, respectively. Changes in water demands for irrigation (Ir) are also input as a time series in the Irrigation module.

The quantity of water demanded for irrigation must be disaggregated from the 6-month (or 3-month) to the daily timestep to be input into HSPF. The quantity of applied nitrogen must also be input into HSPF at the monthly application rate. It is assumed that nitrogen from fertilizer is applied as nitrates ($NO_3^-$) and nitrogen from manure is applied as ammonia ($NH_3$). It is also assumed that nitrogen applied as fertilizer to cropland is input during the month of March while nitrogen applied as fertilizer to pasture is input during the month of August. The sources of irrigation withdrawal are specified within the Irrigation module of HSPF along with the fractions of irrigation demand associated with each source. The fractions of irrigation demand associated with each soil layer are also specified in the Irrigation module. Once all information has been transferred to the modules of HSPF, the model is run again to obtain the watershed results for the scenario being evaluated. The water flow volumes and nitrogen loading results produced by HSPF are again summed to the first timestep.

The objective in these scenarios (characterized in Table 4-2) is to achieve an average nitrogen concentration of 5.0 mg/L or less in the watershed outflow during each timestep to minimize the contribution of this sub-basin to any changes in water quality within Occoquan Reservoir. If this target concentration is not reached, then the nitrogen endowments within the f vector of the economic model are adjusted before running the economic and watershed models again. The coupled models might go through multiple iterations until either the desired nitrogen concentration is achieved in HSPF, or no other feasible solution can be achieved by the economic model, before continuing to the next timestep.

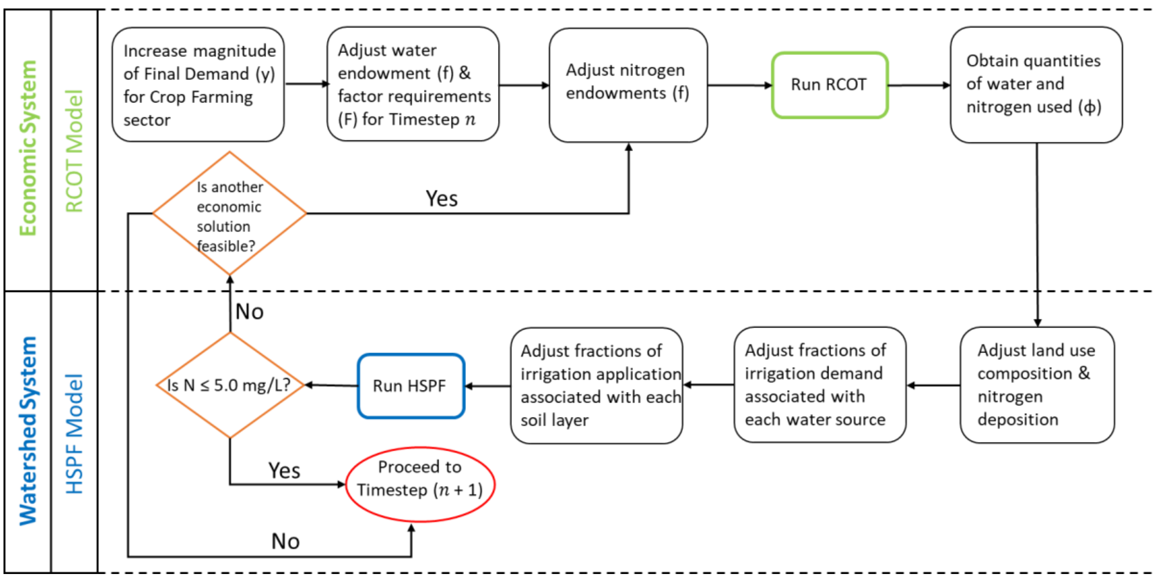


**Figure 4-3.** Decision tree representing steps taken within RCOT and HSPF during Timestep ($n$)

## 4.4 Scenarios

An economic database is assembled to represent Fauquier County under 2012 baseline conditions (see Section 4.3.3). Local monitoring data, collected from 2008 to 2012 has been used to calibrate an HSPF model to represent Cedar Run Watershed by OWML (Bartlett, 2013). Utilizing this data in the coupled hydrologic-economic framework described in Section 4.3, four scenarios are developed to analyze the seasonal impacts of agricultural intensification and irrigation on watershed health. Specifically, the impacts of standard irrigation are compared to the impacts of seasonal conjunctive use in irrigation on water quantity and nitrogen concentration within the outflow of the watershed.

These scenarios, characterized in Table 4-2 and described in more detail in the following sub-sections, are dramatizations based on assumptions about future human activities within Cedar Run Watershed and developed using the Fauquier County database. New agricultural activity is assumed to use irrigation so that the amount of water being removed from the watershed is increased by several orders of magnitude when compared to base year conditions, which made future watershed conditions more extreme but still plausible for Fauquier County. While these scenarios are designed for Fauquier County, they are used to demonstrate the capabilities of the coupled modeling framework, which is intended to be generalizable and used to represent other locations with different water management issues. Examples of the I-O data tables utilized in this scenario analysis are provided in Section C.1 of Appendix C.

**Table 4-2.** Characteristics of scenarios in Chapter 4

| **Scenario Name** | **S1** | **S2** | **S3** | **S4** |
|---|---|---|---|---|
| **Scenario Description** | Agricultural Intensification w/ Irrigation | Agricultural Intensification w/ Irrigation | Agricultural Intensification w/ Irrigation | Agricultural Intensification w/ Irrigation |
| **Timestep** | 6-Month | 3-Month | 6-Month | 3-Month |
| **Irrigation Policy** | Standard Irrigation* | Standard Irrigation* | Conjunctive Use | Conjunctive Use |

*__Source__: Groundwater, **Application Location**: Soil Surface

### 4.4.1 Standard Irrigation (S1 & S2)

Under Scenarios 1 and 2 (referred to as S1 and S2 in Table 4-2), it is assumed that agricultural intensification has occurred within Cedar Run Watershed because of an increase in production for export. The final demand associated with the crop farming sector within the economic system is increased so that all land currently zoned for agricultural activity within the watershed is converted to cropland. It is assumed that all new economic activity is equally distributed among the land segments that make up the watershed and that water is extracted from these segments to be used for agricultural irrigation. Only one irrigation practice is available to the crop farming sector under S1 and S2 because no alternative practices are considered in these scenarios ($t = n$). Specifically, groundwater is withdrawn and applied to the soil surface of the cropland for irrigation use because groundwater is currently the primary source of water within Fauquier County and wells are already present within Cedar Run Watershed. It is also assumed that 40% of the irrigation water applied to the soil surface is intercepted by the crops, which is the value provided by Bicknell et al. (2001) in the HSPF manual. Thus, this irrigation practice is referred to as Standard Irrigation under S1 and S2 in Table 4-2.

Under S1, a 6-month timestep is used (see Table 4-1). It is assumed that 20% of annual water demand is withdrawn during the wet season and 80% of annual water demand is withdrawn during the dry season. It is also assumed that fertilizer for cropland is applied during the month of March, which is part of the wet season, because this month is assumed to be the time of transition between the winter and summer crops. It is assumed that fertilizer for pasture is applied during the month of August, which lies within the dry season. Under S2, a seasonal (3-month) timestep is used instead of a bi-annual timestep. It is assumed that 10% of annual water demand is withdrawn during Winter, Spring, and Fall while the remaining 70% of annual water demand is withdrawn during Summer. It is also assumed that fertilizer for cropland is applied during March, which is part of Winter, and fertilizer for pasture is applied during August, which is part of Summer. Under S1 and S2, it was expected that nitrogen concentration would be increased in the watershed outflow during the wet season and Winter, respectively, because of the fertilizer application and it was also expected that a higher temporal resolution would produce more precise results

### 4.4.2 Implementation of Conjunctive Use (S3 & S4)

Under Scenarios 3 and 4 (referred to as S3 and S4 in Table 4-2), because of an increase in agricultural production, the final demand associated with crop farming is increased so that all land currently zoned for agricultural activity within the watershed is converted to cropland. A bi-annual timestep is utilized under S3 and a seasonal timestep is utilized under S4. Under these scenarios, conjunctive use is introduced into the crop farming sector ($t \geq n$). The primary goal of conjunctive management is to optimize availability and stability of water resources by simultaneously managing groundwater and surface water. Thus, three water sources (groundwater, surface water, or an external water source), distinguished by different factor endowments, specifically water and nitrogen, and three choices in the irrigation location (soil surface, lower soil layer, and active groundwater table) are introduced into RCOT. As a result, nine irrigation options, differing in water source and application location of the irrigation water, are available within the crop farming sector as follows (irrigation source/application location):

1. Groundwater/Soil Surface
2. Groundwater/Lower Soil Layer
3. Groundwater/Active Groundwater Table
4. Surface Water/Soil Surface
5. Surface Water/Lower Soil Layer
6. Surface Water/Active Groundwater Table
7. External Water/Soil Surface
8. External Water/Lower Soil Layer
9. External Water/Active Groundwater Table

These nine irrigation options are also differentiated based on factor price. It is assumed that groundwater is the cheapest source of water since groundwater wells are already being used within the county. An external source of irrigation water is assumed to be the most expensive. Applying irrigation water to the surface layer is assumed to be cheaper than applying the water deeper into the soil layer. There is also an increase in nitrogen loading that is generated because of the excess runoff caused by the implementation of these different irrigation practices. The largest increase in nitrogen loading results from utilizing an external water source for irrigation and the smallest increase results from utilizing surface water for irrigation. These quantities decline as the irrigation is applied deeper into the soil layers and they also vary depending on the season. In these scenarios, it was expected that the source of irrigation water would switch from groundwater to another water source to meet agricultural demand during the first timestep while groundwater would still be used during the other timesteps. Application location was also expected to switch to the sub-surface during the first timestep to minimize the excess nitrogen loading that would occur because of irrigation applied to the soil surface.

### 4.4.3 Results

Scenario results included those produced by the ϕ vector of the economic model (see Table 4-3), which are obtained using a version of the RCOT model programmed using LINGO software (Springer, Duchin, & Levine, 2011). Examples of output data obtained from RCOT in this scenario analysis are included in Sections C.1.8 and C.1.9 of Appendix C. The results produced by the ϕ vector under S3 and S4 are the same as those produced under S1 and S2, respectively, so only the results for S1 and S2 are shown in Table 4-3. As a result of agricultural intensification throughout the watershed, cropland increases by 280% when compared to 2012 base year conditions while jobs increase by 7.8%. Under S1, the quantities of withdrawn water and applied nitrogen increase during the wet season by 86% and 280%, respectively. During the dry season, the quantities of withdrawn water and applied nitrogen increase by 650% and 32%, respectively. Under S2, the quantity of withdrawn water increases by 185% during Winter, Spring, and Fall. During Summer, the quantity of withdrawn water increases by 1303%. The quantity of applied nitrogen increases by 280% during Winter and by 32% during Summer. This information is transferred to HSPF in data tables, for land use (see Section C.2 of Appendix C) and nitrogen deposition (see Section C.3 of Appendix C), and in time series for irrigation demand (see Section C.4 of Appendix C).

**Table 4-3.** Percent (%) increase in factor usage relative to 2012 base year

| | **Season** | **S1** | **Season** | **S2** |
|---|---|---|---|---|
| **Jobs** | Wet | 7.8 | Winter | 7.8 |
| | | | Spring | |
| | Dry | | Summer | |
| | | | Fall | |
| **Cropland** | Wet | 280 | Winter | 280 |
| | | | Spring | |
| | Dry | | Summer | |
| | | | Fall | |
| **Water Withdrawn** | Wet | 86 | Winter | 185 |
| | | | Spring | 185 |
| | Dry | 650 | Summer | 1303 |
| | | | Fall | 185 |
| **Nitrogen Applied** | Wet | 280 | Winter | 280 |
| | | | Spring | 0 |
| | Dry | 32 | Summer | 32 |
| | | | Fall | 0 |

Under S1 and S2, 100% of irrigation water is supplied by groundwater and applied to the soil surface during all timesteps. Additional results include the source and application location of irrigation water selected by RCOT under S3 and S4, which implement conjunctive use (see Table 4-4). Because RCOT is coupled with HSPF, the environmental impacts caused by agricultural expansion in Cedar Run Watershed are captured at the bi-annual and seasonal temporal scales. When choices of conjunctive use are implemented, irrigation strategies are introduced into RCOT, the environmental constraints imposed by the watershed system cause adjustments in management practice within the economic system, which alleviate these seasonal impacts on water quality. Under S3, groundwater applied to the soil surface is utilized during the dry season. During the wet season, 65% of irrigation is supplied by surface water while the remaining 35% is supplied by water imported from outside Cedar Run Watershed. 13% of this irrigation water is applied to the lower soil layer while the remaining 87% is applied directly into the active groundwater table. Under S4, groundwater applied to the soil surface is utilized during all seasons except Winter. During Winter, 65% of irrigation demand is supplied by surface water while the remaining 35% is supplied by a water source external to Cedar Run Watershed. Almost all the irrigation water (99%) is applied directly into the active groundwater table during Winter.

**Table 4-4.** Source and application location of irrigation water during each season

| Scenario | Season | Irrigation Source | | | Application Location | | |
|---|---|---|---|---|---|---|---|
| | | Groundwater | Surface Water | External Water | Surface | Soil Layer | Active Groundwater |
| S3 | Wet | 0 | 65% | 35% | 0 | 13% | 87% |
| | Dry | 100% | 0 | 0 | 100% | 0 | 0 |
| S4 | Winter | 0 | 65% | 35% | 1.0% | 0 | 99% |
| | Spring | 100% | 0 | 0 | 100% | 0 | 0 |
| | Summer | 100% | 0 | 0 | 100% | 0 | 0 |
| | Fall | 100% | 0 | 0 | 100% | 0 | 0 |

Additional scenario results include those produced by HSPF (see Table 4-5), specifically the change in total watershed outflow, caused by the implementation of different irrigation strategies, and the average nitrogen concentration in that outflow. Examples of the output data obtained from HSPF for these scenarios are found in Section C.5 of

Appendix C. Under S1, during the wet season, the average nitrogen concentration increases to 21 mg/L in the watershed outflow while the total outflow reduces by 5.8% because groundwater is exposed to evapotranspiration. Under S2, during Winter, the average nitrogen concentration increases to 35 mg/L in the watershed outflow while the total outflow reduces by 7.4%. During the wet season under S3, the average nitrogen concentration increases to only 5.0 mg/L in the watershed outflow while the outflow quantity increases by 133% due to the use of external water when conjunctive use is implemented. Finally, during Winter under S4, the average nitrogen concentration also increases to only 5.0 mg/L in the watershed outflow while the outflow quantity increases by 156% when conjunctive use is implemented. As indicated by S1 and S2, expanded agricultural activity, irrigated using groundwater applied to the soil surface, causes an increase in nitrogen concentration at the outflow of the watershed during the first timestep, which is unexpectedly high when compared to the other seasons. S3 and S4 indicate that the introduction of conjunctive use allows the increase in nitrogen concentration to be greatly reduced during the first timestep, which is the expected outcome.

**Table 4-5.** Percent increase in total watershed outflow and average total nitrogen (TN) concentration in outflow

| Scenario | Season | Total Outflow (% Increase) | Total Nitrogen Concentration (mg/L) |
|---|---|---|---|
| **S1** | **Wet** | -5.8 | 21 |
| | **Dry** | -11 | 0.7 |
| **S2** | **Winter** | -7.4 | 35 |
| | **Spring** | -4.2 | 2.3 |
| | **Summer** | -6.0 | 0.5 |
| | **Fall** | -8.6 | 0.7 |
| **S3** | **Wet** | 133 | 5.0 |
| | **Dry** | -11 | 0.7 |
| **S4** | **Winter** | 156 | 5.0 |
| | **Spring** | -4.2 | 2.3 |
| | **Summer** | -6.0 | 0.5 |
| | **Fall** | -8.6 | 0.7 |

## 4.5 Discussion

The implementation of conjunctive use alleviates the seasonal elevations in nitrogen concentration caused by agricultural intensification and irrigation in Cedar Run Watershed. Under S1 and S2, the nitrogen concentration within the watershed outflow increases significantly during the first timestep (21 and 35 mg/L, respectively) because fertilizer is applied to the soil surface and, during some years, the surface runoff is high enough during that season to wash off the fertilizer into the channel reaches. Specifically, nitrogen concentration increases significantly when fertilizer is applied during times of high flow rates within the watershed. Because of the unusually high concentration of nitrogen present in the groundwater, the utilization of groundwater irrigation also further increases the nitrogen concentration in the watershed outflow during the first timestep. This high nitrogen concentration in the groundwater could be caused by failing septic systems resulting from aging infrastructure, which have been cited as an issue in Fauquier County (Fauquier County Board of Supervisors, 2019). Applying irrigation water to the soil surface, as is done under S1 and S2, also results in an increase in surface runoff, which also contributes to the increase in nitrogen loading into the watershed outflow during the first timestep. When conjunctive use is introduced under S3 and S4, the nitrogen concentration in the watershed outflow is significantly reduced to 5.0 mg/L in the first timestep when compared to the results of S1 and S2, respectively. This reduction occurs because surface and externally sourced water applied to the subsurface of the cropland is selected among the alternatives explicitly considered as the most efficient solution to satisfy the objective functions during the first timestep. Specifically, this selection in irrigation practice minimizes the nitrogen runoff generated by the crop farming sector of the economy.

Increasing the temporal resolution to a seasonal timestep produces different results than a bi-annual timestep. When a bi-annual timestep is utilized under S3, the concentration of nitrogen in the outflow of Cedar Run Watershed can achieve a nitrogen concentration of 5.0 mg/L, which was specified as the objective for the coupled modeling framework. When a seasonal timestep is utilized under S4, the concentration of nitrogen in the outflow of Cedar Run Watershed can also meet the raw water requirement during Winter, but different conjunctive use strategies are identified as the most efficient of those considered when different sub-annual timesteps are used. Under both S3 and S4, nitrogen is applied to the cropland during the month of March, but the lower temporal resolution under S3 results in the dilution of this applied nitrogen across a 6-month period rather than a 3-month period as was the case under S4. Thus, the resolution of the sub-annual timestep must be carefully considered when coupling the economic and watershed models because the implications of different management decisions will vary depending on the timestep that is selected.

New agricultural activity can require a time-varying distribution of resources, such as water and applied nitrogen, which results in varying impacts on watershed health depending on the time of the year and depending on the management practices selected within the agricultural sector of the economy. The nitrogen concentration increases significantly during one season and then remains low during the remainder of the year. Capturing these seasonal environmental impacts on watershed health requires the temporal disaggregation of I-O data tables, but available databases tend to be aggregated to the annual time scale (Sun et al., 2019). As a result, previous I-O studies have focused on inter-year temporal development rather than intra-year temporal scales (Avelino, 2017). However, RCOT has unique features that allow for management options for all sectors of the economy and minimize the use of resources based on environmental constraints imposed by the watershed, which grounds human decisions in a region's physical reality (Amaya et al., 2021). Thus, by coupling RCOT with a continuous watershed model, HSPF, at a sub-annual temporal scale, this coupled modeling framework captures the seasonality of interactions between the economic and watershed systems. These interactions are captured at a level of temporal detail that expands the range of questions that can be addressed by both economists and hydrologists beyond those that can be analyzed using these models individually. However, it is necessary to consider the uncertainty intrinsic in these models, such as the uncertainty associated with the empirical relationships between variables and the uncertainty of the assumptions (Settre, Connor, & Wheeler, 2016). These uncertainties might be compounded when these models are coupled, but some uncertainty could be removed since assumptions may be better informed using this framework. In these initial studies, this modeling framework serves its intended purpose and future studies can be untaken to reduce uncertainty.

### 4.5.1 Conclusions

The intensification of irrigated agriculture has seasonal impacts on nitrogen concentration within the outflow of Cedar Run Watershed. Conjunctive use is a viable management practice to alleviate the seasonality of nitrogen concentration elevation caused by the expansion of agricultural activity within Cedar Run Watershed. When coupling watershed and economic systems, the temporal units must be carefully considered because the implications of different management decisions will vary depending on the timestep that is selected. If economic I-O data is collected at sub-annual temporal scales, then this modeling framework can provide insight into the interactions between watershed and economic systems at temporal units best suited for questions being addressed in empirical studies.

### 4.5.2 Future Work

The coupled hydrologic-economic modeling framework will be applied to other locations with critical environmental issues and an economy that is different from that of Fauquier County. This modeling framework could also be used to examine the impacts of changing climate conditions on the coupled watershed and economic systems. Full-scale empirical studies using the WTM/RCOT model, developed by Duchin and Levine (2012), coupled with a watershed model like HSPF, would make it possible to study a region, such as Chesapeake Bay Watershed, by representing the ensemble of sub-watershed economic regions, the economic relations among them, and their interactions with the watershed at a suitable temporal resolution. For future studies, models representing social system will also be integrated into this coupled modeling framework since this modular framework is appropriate for a system-of-systems approach that incorporates different models from different disciplines to better represent a socio-environmental system and inform policy decisions (Iwanaga et al., 2021; Little, Hester, & Carey, 2016; Little et al., 2019).

## 4.6 Acknowledgments

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# Chapter 5 Conclusions

## 5.1 Research Summary

Economic models and watershed models provide useful results, but when seeking to integrate these systems, the structural, spatial, and temporal differences between these models must be carefully considered. In this research, a hydrologic-economic modeling framework, which couples an economic model with a watershed model, is designed to reconcile these differences. A physically constrained, input-output (I-O) model, RCOT, is used to represent the economic system in this modeling framework because it allows for technology options for all sectors of the economy and minimizes the use of resources based on environmental constraints imposed by the watershed. To represent the watershed system in this modeling framework, the Hydrological Simulation Program-Fortran (HSPF) model is used. An HSPF model has been calibrated to represent the hydrological processes of Cedar Run Watershed by the Occoquan Watershed Monitoring Laboratory (OWML). Thus, to demonstrate the capabilities of this modeling framework, strategic scenarios are developed to examine alternative future development patterns that may occur within Fauquier County, located in northern Virginia, their impacts on water flow and nitrogen concentration in the local basin, Cedar Run Watershed, and the changes made within the economic system in response to these impacts.

In the first paper, to demonstrate the potential of linking RCOT and HSPF in a coupled framework, eight simple scenarios are developed relating to the expansion of agricultural activity in Fauquier County. The database for RCOT uses county-level input-output data representative of the region in 2012. When crop farming is expanded to fully utilize the farmland available in the watershed, the nitrogen concentration at the outflow of the watershed increases from 0.6 to 4.3 mg/L. However, when RCOT could select between a standard and a more nitrogen-efficient management practice, the outflow nitrogen concentration only increased to 2.2 mg/L because RCOT selects the more resource-efficient practice.

In the second paper, this coupled modeling framework is used to demonstrate that bringing HSPF and RCOT together can address questions relevant to both economists and hydrologists, beyond purely administrative or watershed concerns. Thus, this framework is utilized to assess the implications of alternative future development prospects within Fauquier County, northern Virginia, specifically residential build-up, and agricultural intensification in the upstream region of the local watershed. Four scenarios are designed to evaluate the downstream impacts on watershed health caused by upstream development and changes made within the economic sectors in response to these impacts.

In the third paper, this modeling framework is implemented at different sub-annual timesteps to gain insight in selecting temporal units best suited for addressing questions of interest to both economists and hydrologists. Four scenarios are designed to examine the seasonal increases in nitrogen concentration that occur because of agricultural intensification within Cedar Run Watershed, located in Fauquier County, northern Virginia. These scenarios also evaluate the selection among alternative conjunctive use practices for irrigation within the crop farming sector in response to these seasonal impacts. The most efficient of the considered conjunctive use strategies varies depending on which timestep is utilized in the scenario: a bi-annual timestep (wet and dry season) versus a seasonal timestep.

Coupling HSPF with RCOT can capture the human decisions made within the economic system in response to environmental constraints imposed by the watershed, which are choices that may be made to maximize efficiency. By linking RCOT with HSPF, the environmental impacts of these choices can also be examined. This coupled hydrologic-economic modeling framework has the capacity to overcome the spatial differences of the individual models and capture the interactions between watershed and economic systems at a temporal resolution that expands the range of questions one can address beyond those that can be analyzed using the individual models linked in this framework. Thus, this research brings a multi-disciplinary perspective to identify pathways for addressing water use and contamination while also supporting economic progress to achieve sustainable development.

## 5.2 Summary of Key Findings

The key findings of this research are summarized in the following points:

- A framework that couples economic and watershed systems can capture the interactions between these two systems and can also be used to analyze how changes in economic activity will impact watershed health, but selecting the appropriate economic model requires careful consideration and more detailed information can be obtained depending on which model is utilized.
- When RCOT is coupled with HSPF, information can be obtained about how choices in technology, seeking to minimize the use of resource inputs, can influence economic activity and alter impacts on watershed health, which are realistic decisions made within the economic system and, by linking RCOT with HSPF, the environmental impacts of these choices can be examined.
- In the case of upstream residential build-up in Cedar Run Watershed, an alternative technology is more efficient than the standard technology for providing water for upstream residents while ensuring an adequate water supply in the downstream location.
- When upstream agricultural intensification occurs in Cedar Run Watershed, a shift in crops from grains to fruits and vegetables, which are higher-value crops, is the most efficient of the alternatives considered.
- Collecting spatially resolved, input-output and hydrological data enables this systems research applied in truly empirical studies to a variety of watersheds in other physical and societal contexts.
- When agricultural intensification occurs in Cedar Run Watershed, implementing conjunctive use in irrigation reduces the seasonal increases in nitrogen concentration to specified limits.
- When coupling watershed and economic systems, the temporal units must be carefully considered because the implications of different management decisions will vary depending on the timestep that is selected.
- Collecting economic I-O data at sub-annual temporal scales allows this modeling framework to provide insight into the interactions between watershed and

economic systems at temporal units best suited for questions being addressed in full-scale empirical studies.

## 5.3 Recommendations for Future Work

While this research demonstrates the capabilities of the coupled hydrologic-economic modeling framework and provides insight into the implications of alternative future development prospects that may occur in Fauquier County, recommended pathways for future research are as follows:

- Apply this modeling framework in full-scale empirical studies of several other watersheds with compelling environmental concerns and economic sectors that are different from those present in Fauquier County to see similarities and differences.
- Use this framework to examine the impacts of changing climate conditions on the coupled watershed and economic systems in different regions, such as in locations where rainfall is expected to increase over shorter periods of time or where droughts are expected to become more extreme.
- Analyze inter-regional impacts using the World Trade Model (WTM) and RCOT, linked with a watershed model, such as HSPF, to study a region, such as Chesapeake Bay Watershed, by representing the ensemble of sub-watershed economic regions and the economic relations among them at the county level using WTM, linked with a model of the entire watershed with the necessary spatial disaggregation.
- Conduct a sensitivity analysis to evaluate the uncertainty inherent in this modular framework, including in the individual models that are linked in this framework, and determine how this uncertainty can be reduced.
- Incorporate social systems into the hydrologic-economic modeling framework for future studies because this modular framework is suitable for a system-of-systems approach that integrates different models from across disciplines to better represent a socio-environmental system that can be used to inform decisions.

## Appendix A

Appendix A provides example data tables representative of those used for scenario analysis in Chapter 2. These data tables include those input into and output from both RCOT and HSPF. The data are used in illustrative scenarios, which are developed to demonstrate the capabilities of the coupled modeling framework.

### A.1 Input-Output Data Tables

This study requires the construction of a county-level database to represent Fauquier County's economy and to distinguish between the sectors of interest for this analysis. Fortunately, monetary county-level, input-output data is available from a private company called IMPLAN Group, LLC. IMPLAN Group compiles their county-level datasets by gathering data from various sources, including the United States Bureau of Economic Analysis (BEA) and Bureau of Labor Statistics (BLS), and providing estimates for unavailable data while benchmarking them against other data to ensure as much accuracy as possible. Economic data is obtained for Fauquier County representative of the year 2012, which serves as the base year. To begin, the county input-output transaction table (Z) and industry final demand data (y) provided by IMPLAN Group are aggregated into seven basic industrial sectors. These sectors, including agriculture, mining, construction, manufacturing, utilities, professional services, and government services, are aggregated based on the North American Industry Classification System (NAICS) established by the United States Census Bureau (2017). Once the transaction table is aggregated, the technical coefficient (A) matrix is calculated using the data from the transaction table and economic output data provided by IMPLAN Group. Next, the agriculture sector is disaggregated into three specific sectors, crop farming, animal husbandry, and other agricultural activities, for a more detailed analysis. Total sector output is calculated for the 2012 base year using this A matrix as well as the aggregated final demand ($y$) vector. The resulting output (x) vector is compared to the sector output data provided by IMPLAN Group for 2012 to verify that this model accurately represents the economy of Fauquier County. The results produced by the model are within the same range as the provided data.

To build the factor requirement per unit of output (F*) matrix, six factors of production are identified as requirements for each sector, specifically land, labor, capital, water withdrawn, nitrogen applied as fertilizer and nitrogen applied as manure. Annual labor and capital requirements are calculated using IMPLAN sectoral data for labor, capital, and economic output. Water withdrawn per unit of output for each sector is determined using county water data available from the United States Geological Survey (USGS, 2010) and data obtained from an input-output database assembled by the Green Design Institute at Carnegie Mellon University (Blackhurst, Hendrickson & Vidal, 2010). Additionally, fertilizer requirements are assumed based on county data available from the National Agricultural Statistics Service (NASS). Furthermore, land requirements per sector are assumed based on county zoning data provided by the Fauquier County GIS Office (2014). Land cover data obtained from the Virginia Geographic Information Network (VGIN, 2016) is used in combination with the zoning data to determine how much land in each zone is cleared or wooded, which is assumed to be an indicator of developed and undeveloped land, respectively.

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## A.1.1 Coefficient ($A^*$) Matrix

**Table A-1.** Coefficient ($A^*$) matrix used for base year and Scenario 1 of Chapter 2

| | Crop Farming | Animal Husbandry | Other Agricultural Activities | Mining | Construction | Manufacturing | Trade, Transportation Utilities | Professional Services | Government Services |
|---|---|---|---|---|---|---|---|---|---|
| **Crop Farming** | 0.0376 | 0.0001 | 0.0129 | 0.0001 | 0.0002 | 0.0029 | 0.0000 | 0.0000 | 0.0000 |
| **Animal Husbandry** | 0.0683 | 0.1058 | 0.0246 | 0.0001 | 0.0003 | 0.0055 | 0.0000 | 0.0000 | 0.0000 |
| **Other Agricultural Activities** | 0.0115 | 0.0115 | 0.0758 | 0.0001 | 0.0003 | 0.0054 | 0.0000 | 0.0000 | 0.0000 |
| **Mining** | 0.0009 | 0.0009 | 0.0009 | 0.0153 | 0.0058 | 0.0004 | 0.0030 | 0.0003 | 0.0006 |
| **Construction** | 0.0047 | 0.0047 | 0.0047 | 0.0516 | 0.0003 | 0.0031 | 0.0043 | 0.0170 | 0.0111 |
| **Manufacturing** | 0.0005 | 0.0005 | 0.0005 | 0.0001 | 0.0088 | 0.0019 | 0.0020 | 0.0012 | 0.0001 |
| **Trade, Transportation, Utilities** | 0.0432 | 0.0432 | 0.0432 | 0.0341 | 0.0789 | 0.0466 | 0.0418 | 0.0175 | 0.0016 |
| **Professional Services** | 0.0446 | 0.0446 | 0.0446 | 0.1088 | 0.0562 | 0.0622 | 0.1350 | 0.1723 | 0.0109 |
| **Government Services** | 0.0017 | 0.0017 | 0.0017 | 0.0008 | 0.0003 | 0.0017 | 0.0084 | 0.0021 | 0.0003 |

## A.1.2 Factor Requirement ($F^*$) Matrix

**Table A-2.** Factor Requirement ($F^*$) matrix used for base year and Scenario 1 of Chapter 2

| | Crop Farming (/$M) | Animal Husbandry (/$M) | Other Agricultural Activities (/$M) | Mining (/$M) | Construction (/$M) | Manufacturing (/$M) | Trade, Transportation, Utilities (/$M) | Professional Services (/$M) | Government Services (/$M) |
|---|---|---|---|---|---|---|---|---|---|
| **Labor (employees)** | 38.47 | 25.02 | 15.77 | 3.81 | 6.21 | 2.64 | 8.78 | 7.72 | 10.11 |
| **Capital ($M)** | 0.00 | 0.00 | 0.00 | 0.02 | 0.63 | 0.00 | 0.06 | 0.05 | 0.00 |
| **Land Use (ac)** | 1681.96 | 3758.17 | 1582.45 | 14.52 | 1.05 | 2.76 | 0.37 | 0.18 | 0.97 |
| **Water Withdrawal (MG)** | 7.64 | 9.48 | 0.00 | 2.68 | 0.37 | 10.46 | 0.16 | 0.18 | 1.33 |
| **$NO_3^-$ Applied as Fertilizer (short tons)** | 70.99 | 7.46 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **$NH_3$ Applied as Manure (short tons)** | 0.00 | 5.46 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

### A.1.5 Final Demand (y) Vectors

**Table A-3.** Final Demand (y) vector used for base year of Chapter 2

| | |
|---|---|
| **Crop Farming ($M)** | 6.25 |
| **Animal Husbandry ($M)** | 2.48 |
| **Other Agricultural Activities ($M)** | 2.94 |
| **Mining ($M)** | 9.65 |
| **Construction ($M)** | 0.00 |
| **Manufacturing ($M)** | 222.26 |
| **Trade, Transportation, Utilities ($M)** | 172.98 |
| **Professional Services ($M)** | 494.03 |
| **Government Services ($M)** | 266.98 |

**Table A-4.** Final Demand (y) vector used for Scenario 1 of Chapter 2

| | |
|---|---|
| **Crop Farming ($M)** | 25.67 |
| **Animal Husbandry ($M)** | 2.48 |
| **Other Agricultural Activities ($M)** | 2.94 |
| **Mining ($M)** | 9.65 |
| **Construction ($M)** | 0.00 |
| **Manufacturing ($M)** | 222.26 |
| **Trade, Transportation, Utilities ($M)** | 172.98 |
| **Professional Services ($M)** | 494.03 |
| **Government Services ($M)** | 266.98 |

### A.1.6 Factor Endowment (f) Vector

**Table A-5.** Factor Endowment (f) vector used for Scenario 1 of Chapter 2

| | |
|---|---|
| **Labor (employees)** | 36000 |
| **Capital ($M)** | 530 |
| **Land Use (ac)** | 81465 |
| **Water Withdrawal (MG)** | 35304 |
| **$NO_3^-$ Applied as Fertilizer (short tons)** | 3490 |
| **$NH_3$ Applied as Manure (short tons)** | 164 |

### A.1.7 Factor Price (π) Vector

**Table A-6.** Factor Price (π) vector used for base year and Scenario 1 of Chapter 2

| | |
|---|---|
| **Wages ($/employee)** | 45,792 |
| **Payment to Capital ($/$M)** | 10,000 |
| **Land Rent ($/ac)** | 26 |
| **Water Billing Rate ($/MG)** | 60,072 |
| **Fertilizer Cost ($/short ton)** | 574 |
| **Manure Cost ($/short ton)** | 0 |

### A.1.8 Economic Output ($x^*$) Vectors

**Table A-7.** Economic Output ($x^*$) vector obtained for base year of Chapter 2

| | |
|---|---|
| **Crop Farming ($M)** | 7.47 |
| **Animal Husbandry ($M)** | 4.88 |
| **Other Agricultural Activities ($M)** | 4.68 |
| **Mining ($M)** | 10.80 |
| **Construction ($M)** | 16.33 |
| **Manufacturing ($M)** | 224.10 |
| **Trade, Transportation, Utilities ($M)** | 206.32 |
| **Professional Services ($M)** | 654.36 |
| **Government Services ($M)** | 270.58 |

**Table A-8.** Economic Output ($x^*$) vector obtained for Scenario 1 of Chapter 2

| | |
|---|---|
| **Crop Farming ($M)** | 27.98 |
| **Animal Husbandry ($M)** | 6.41 |
| **Other Agricultural Activities ($M)** | 4.95 |
| **Mining ($M)** | 10.98 |
| **Construction ($M)** | 16.47 |
| **Manufacturing ($M)** | 224.11 |
| **Trade, Transportation, Utilities ($M)** | 207.35 |
| **Professional Services ($M)** | 655.74 |
| **Government Services ($M)** | 270.62 |

### A.1.9 Factor Use (φ) Vectors

**Table A-9.** Factor Use (φ) vector obtained for base year of Chapter 2

| | |
|---|---|
| **Labor (employees)** | 10814 |
| **Capital ($M)** | 58 |
| **Land Use (ac)** | 39576 |
| **Water Withdrawal (MG)** | 2993 |
| **$NO_3^-$ Applied as Fertilizer (short tons)** | 567 |
| **$NH_3$ Applied as Manure (short tons)** | 27 |

**Table A-10.** Factor Use (φ) vector obtained for Scenario 1 of Chapter 2

| | |
|---|---|
| **Labor (employees)** | 11655 |
| **Capital ($M)** | 58 |
| **Land Use (ac)** | 79772 |
| **Water Withdrawal (MG)** | 3163 |
| **$NO_3^-$ Applied as Fertilizer (short tons)** | 2011 |
| **$NH_3$ Applied as Manure (short tons)** | 35 |

## A.2 Land Use Data Tables

**Table A-11.** Land Use table in SCHEMATIC module for base year of Chapter 2

| # | Segment | Pasture | Forest | Low Density Res. | Low Till. Corps | High Till. Corps | Industrial | Institutional | Medium Density Res. | Townhouse/ garden apt. | Sum |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Land Use (Acre) | | | | | | | | | |
| PERLND | | | | | | | | | | | |
| 1 | 29 | 188.0 | 2527.1 | 1219.9 | 65.3 | 341.6 | 13.4 | 6.5 | 9.1 | 2.2 | 4373.1 |
| 2 | 30 | 1702.1 | 7509.5 | 1240.3 | 610.3 | 427.8 | 110.9 | 130.0 | 721.8 | 100.8 | 12553.5 |
| 3 | 34 | 12.2 | 430.7 | 254.6 | 0.0 | 0.0 | | | | | 697.5 |
| 4 | 35 | 994.3 | 4010.5 | 717.1 | 1271.4 | 481.5 | 10.3 | 103.3 | | | 7588.3 |
| 5 | 36 | 428.1 | 14775.7 | 855.7 | 710.4 | 9.1 | | 93.9 | | | 16872.8 |
| 6 | 37 | 1046.4 | 2934.2 | 600.0 | 669.6 | 501.9 | 1.4 | 1.5 | 50.2 | | 5805.2 |
| 7 | 38 | 1587.4 | 5359.7 | 624.8 | 1629.6 | 639.3 | 183.2 | 73.1 | 82.8 | 15.0 | 10194.8 |
| 8 | 39 | 732.0 | 1715.0 | 166.4 | 645.1 | 566.7 | 37.5 | 14.9 | | | 3877.7 |
| 9 | 40 | 764.9 | 4125.1 | 304.1 | 1151.3 | 2372.0 | 57.7 | 7.9 | | | 8783.0 |
| 10 | 41 | 954.1 | 5921.1 | 386.3 | 1024.9 | 1224.7 | 19.6 | 40.3 | 13.0 | | 9583.9 |
| 11 | 42 | 315.0 | 1129.2 | 90.1 | 303.6 | 1450.8 | 4.5 | 2.3 | 1.4 | | 3296.9 |
| 12 | 43 | 349.8 | 6290.3 | 452.8 | 871.9 | 4346.9 | | 7.4 | | | 12319.1 |
| 13 | 44 | 243.4 | 6885.9 | 425.4 | 197.2 | 1396.0 | 4.5 | 1.2 | | | 9153.5 |
| 14 | 47 | 199.7 | 2899.7 | 89.4 | 496.3 | 505.7 | 6.4 | 1.0 | | | 4198.2 |
| 15 | 55 | 1327.8 | 6413.5 | 845.7 | 972.4 | 797.4 | 43.8 | 72.1 | 21.2 | | 10494.0 |
| Sub-Total | | 11964.6 | 65279.9 | 8272.5 | 13883.2 | 18325.3 | 493.1 | 555.5 | 899.5 | 118.1 | 119791.5 |
| IMPLND | | | | | | | | | | | |
| 1 | 29 | 1.9 | 25.5 | 135.5 | 1.3 | 7.0 | 13.4 | 3.5 | 2.3 | 1.2 | 191.6 |
| 2 | 30 | 17.2 | 75.9 | 137.8 | 12.5 | 8.7 | 110.9 | 70.0 | 180.4 | 54.3 | 667.7 |
| 3 | 34 | 0.1 | 4.4 | 28.3 | | | | | | | 32.8 |
| 4 | 35 | 10.0 | 40.5 | 79.7 | 25.9 | 9.8 | 10.3 | 55.6 | | | 232.0 |
| 5 | 36 | 4.3 | 149.2 | 95.1 | 14.5 | 0.2 | | 50.6 | | | 313.9 |
| 6 | 37 | 10.6 | 29.6 | 66.7 | 13.7 | 10.2 | 1.4 | 0.8 | 12.5 | | 145.6 |
| 7 | 38 | 16.0 | 54.1 | 69.4 | 33.3 | 13.0 | 183.2 | 39.3 | 20.7 | 8.1 | 437.2 |
| 8 | 39 | 7.4 | 17.3 | 18.5 | 13.2 | 11.6 | 37.5 | 8.0 | | | 113.5 |
| 9 | 40 | 7.7 | 41.7 | 33.8 | 23.5 | 48.4 | 57.7 | 4.3 | | | 217.0 |
| 10 | 41 | 9.6 | 59.8 | 42.9 | 20.9 | 25.0 | 19.6 | 21.7 | 3.2 | | 202.8 |
| 11 | 42 | 3.2 | 11.4 | 10.0 | 6.2 | 29.6 | 4.5 | 1.3 | 0.4 | | 66.5 |
| 12 | 43 | 3.5 | 63.5 | 50.3 | 17.8 | 88.7 | | 4.0 | | | 227.9 |
| 13 | 44 | 2.5 | 69.6 | 47.3 | 4.0 | 28.5 | 4.5 | 0.6 | | | 156.9 |
| 14 | 47 | 2.0 | 29.3 | 9.9 | 10.1 | 10.3 | 6.4 | 0.5 | | | 68.6 |
| 15 | 55 | 13.4 | 64.8 | 94.0 | 19.8 | 16.3 | 43.8 | 38.8 | 5.3 | | 296.2 |
| Sub-Total | | 109.5 | 736.6 | 919.2 | 216.7 | 307.4 | 493.1 | 299.1 | 224.9 | 63.6 | 3370.1 |
| Total | | 12074.1 | 66016.5 | 9191.6 | 14099.9 | 18632.6 | 986.2 | 854.6 | 1124.3 | 181.6 | 123161.6 |

**Table A-12.** Land Use table in SCHEMATIC module for Scenario 1 of Chapter 2

| # | Segment | Pasture | Forest | Low Density Res. | Low Till. Corps | High Till. Corps | Industrial | Institutional | Medium Density Res. | Townhouse/ garden apt. | Sum |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Land Use (Acre) | | | | | | | | | |
| PERLND | | | | | | | | | | | |
| 1 | 29 | 673.0 | 0.0 | 1219.9 | 1086.3 | 1362.6 | 13.4 | 6.5 | 9.1 | 2.2 | 4373.1 |
| 2 | 30 | 2187.2 | 3429.2 | 1240.3 | 2407.9 | 2225.4 | 110.9 | 130.0 | 721.8 | 100.8 | 12553.5 |
| 3 | 34 | 12.2 | 430.7 | 254.6 | 0.0 | 0.0 | | | | | 697.5 |
| 4 | 35 | 994.3 | 4010.5 | 717.1 | 1271.4 | 481.5 | 10.3 | 103.3 | | | 7588.3 |
| 5 | 36 | 428.1 | 14775.7 | 855.7 | 710.4 | 9.1 | | 93.9 | | | 16872.8 |
| 6 | 37 | 1531.4 | 0.0 | 600.0 | 1894.1 | 1726.5 | 1.4 | 1.5 | 50.2 | | 5805.2 |
| 7 | 38 | 2072.4 | 1279.5 | 624.8 | 3427.2 | 2436.9 | 183.2 | 73.1 | 82.8 | 15.0 | 10194.8 |
| 8 | 39 | 1217.1 | 0.0 | 166.4 | 1260.1 | 1181.7 | 37.5 | 14.9 | | | 3877.7 |
| 9 | 40 | 1250.0 | 44.9 | 304.1 | 2948.9 | 4169.6 | 57.7 | 7.9 | | | 8783.0 |
| 10 | 41 | 1439.1 | 1840.9 | 386.3 | 2822.5 | 3022.3 | 19.6 | 40.3 | 13.0 | | 9583.9 |
| 11 | 42 | 800.0 | 0.0 | 90.1 | 625.7 | 1772.9 | 4.5 | 2.3 | 1.4 | | 3296.9 |
| 12 | 43 | 834.9 | 2210.1 | 452.8 | 2669.5 | 6144.5 | | 7.4 | | | 12319.1 |
| 13 | 44 | 728.5 | 2805.7 | 425.4 | 1994.8 | 3193.5 | 4.5 | 1.2 | | | 9153.5 |
| 14 | 47 | 684.8 | 0.0 | 89.4 | 1703.6 | 1713.1 | 6.4 | 1.0 | | | 4198.2 |
| 15 | 55 | 1812.8 | 2333.3 | 845.7 | 2770.0 | 2595.0 | 43.8 | 72.1 | 21.2 | | 10494.0 |
| Sub-Total | | 16665.7 | 33160.4 | 8272.5 | 27592.3 | 32034.4 | 493.1 | 555.5 | 899.5 | 118.1 | 119791.5 |
| IMPLND | | | | | | | | | | | |
| 1 | 29 | 1.9 | 25.5 | 135.5 | 1.3 | 7.0 | 13.4 | 3.5 | 2.3 | 1.2 | 191.6 |
| 2 | 30 | 17.2 | 75.9 | 137.8 | 12.5 | 8.7 | 110.9 | 70.0 | 180.4 | 54.3 | 667.7 |
| 3 | 34 | 0.1 | 4.4 | 28.3 | | | | | | | 32.8 |
| 4 | 35 | 10.0 | 40.5 | 79.7 | 25.9 | 9.8 | 10.3 | 55.6 | | | 232.0 |
| 5 | 36 | 4.3 | 149.2 | 95.1 | 14.5 | 0.2 | | 50.6 | | | 313.9 |
| 6 | 37 | 10.6 | 29.6 | 66.7 | 13.7 | 10.2 | 1.4 | 0.8 | 12.5 | | 145.6 |
| 7 | 38 | 16.0 | 54.1 | 69.4 | 33.3 | 13.0 | 183.2 | 39.3 | 20.7 | 8.1 | 437.2 |
| 8 | 39 | 7.4 | 17.3 | 18.5 | 13.2 | 11.6 | 37.5 | 8.0 | | | 113.5 |
| 9 | 40 | 7.7 | 41.7 | 33.8 | 23.5 | 48.4 | 57.7 | 4.3 | | | 217.0 |
| 10 | 41 | 9.6 | 59.8 | 42.9 | 20.9 | 25.0 | 19.6 | 21.7 | 3.2 | | 202.8 |
| 11 | 42 | 3.2 | 11.4 | 10.0 | 6.2 | 29.6 | 4.5 | 1.3 | 0.4 | | 66.5 |
| 12 | 43 | 3.5 | 63.5 | 50.3 | 17.8 | 88.7 | | 4.0 | | | 227.9 |
| 13 | 44 | 2.5 | 69.6 | 47.3 | 4.0 | 28.5 | 4.5 | 0.6 | | | 156.9 |
| 14 | 47 | 2.0 | 29.3 | 9.9 | 10.1 | 10.3 | 6.4 | 0.5 | | | 68.6 |
| 15 | 55 | 13.4 | 64.8 | 94.0 | 19.8 | 16.3 | 43.8 | 38.8 | 5.3 | | 296.2 |
| Sub-Total | | 109.5 | 736.6 | 919.2 | 216.7 | 307.4 | 493.1 | 299.1 | 224.9 | 63.6 | 3370.1 |
| Total | | 12074.1 | 66016.5 | 9191.6 | 14099.9 | 18632.6 | 986.2 | 854.6 | 1124.3 | 181.6 | 123161.6 |

## A.3 Nitrogen Deposition Data Tables

**Table A-13.** Nitrogen Deposition table in PQUAL module for base year of Chapter 2

| | Jan | Feb | March | April | May | June | July | August | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pasture, $NH_3$ (lb/ac)** | 1.60E-04 | 1.60E-04 | 1.40E-04 | 1.40E-04 | 1.40E-04 | 1.20E-04 | 1.20E-04 | 1.20E-04 | 1.10E-04 | 1.10E-04 | 1.10E-04 | 1.60E-04 |
| **Pasture, $NO_3^-$ (lb/ac)** | 2.60E-04 | 2.60E-04 | 3.00E-04 | 3.00E-04 | 3.00E-04 | 1.90E-04 | 1.90E-04 | 1.90E-04 | 2.50E-04 | 2.50E-04 | 2.50E-04 | 2.60E-04 |
| **Cropland, $NO_3^-$ (lb/ac)** | 2.60E-04 | 2.60E-04 | 3.00E-04 | 3.00E-04 | 3.00E-04 | 1.90E-04 | 1.90E-04 | 1.90E-04 | 2.50E-04 | 2.50E-04 | 2.50E-04 | 2.60E-04 |

**Table A-14.** Nitrogen Deposition table in PQUAL module for Scenario 1 of Chapter 2

| | Jan | Feb | March | April | May | June | July | August | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pasture, $NH_3$ (lb/ac)** | 8.18E-02 | 8.18E-02 | 8.18E-02 | 8.18E-02 | 8.18E-02 | 8.18E-02 | 8.18E-02 | 8.18E-02 | 8.18E-02 | 8.18E-02 | 8.18E-02 | 8.18E-02 |
| **Pasture, $NO_3^-$ (lb/ac)** | 2.60E-04 | 2.60E-04 | 3.00E-04 | 3.00E-04 | 3.00E-04 | 1.90E-04 | 1.90E-04 | 1.34E+00 | 2.50E-04 | 2.50E-04 | 2.50E-04 | 2.60E-04 |
| **Cropland, $NO_3^-$ (lb/ac)** | 2.60E-04 | 2.60E-04 | 4.73E+01 | 3.00E-04 | 3.00E-04 | 1.90E-04 | 1.90E-04 | 1.90E-04 | 2.50E-04 | 2.50E-04 | 2.50E-04 | 2.60E-04 |

## A.4 Watershed Output Results

### A.4.1 Water Outflow Volumes

**Table A-15.** Average annual outflow from watershed ($ft^3/yr$) obtained from HSPF for Scenarios of Chapter 2

| | |
|---|---|
| **Baseline** | 4,320,234,892 |
| S1 | 4,329,383,937 |
| S2 | 4,442,406,859 |
| S3 | 4,334,201,359 |
| S4 | 4,470,631,699 |
| S5 | 4,365,696,650 |
| S6 | 4,443,171,253 |
| S7 | 4,334,201,359 |
| S8 | 4,443,171,253 |

### A.4.2 Nitrogen Loadings

**Table A-16.** Average annual total nitrogen loading (kg/yr) in outflow from watershed obtained from HSPF for Scenarios of Chapter 2

| | |
|---|---|
| **Baseline** | 64,877 |
| **S1** | 532,269 |
| **S2** | 86,898 |
| **S3** | 510,773 |
| **S4** | 88,299 |
| **S5** | 268,888 |
| **S6** | 86,034 |
| **S7** | 510,773 |
| **S8** | 87,704 |

## Appendix B

Appendix B provides example data tables representative of those used for scenario analysis in Chapter 3. These data tables include those input into and output from both RCOT and HSPF. The data are used in illustrative scenarios, which are developed to demonstrate the capabilities of the coupled modeling framework.

### B.1 Input-Output Data Tables

An economic database representative of Fauquier County had to be constructed for use in RCOT. To construct the database for this study, sectoral economic data, representative of base year 2012, are obtained for the county. 2012 was selected as the base year because the most complete database that could be assembled for this county is representative of this year. Monetary county-level, input-output data and industry final demand data based on national accounts are provided by a private company called IMPLAN Group, LLC [1]. To compile their I-O datasets, IMPLAN obtains data from different government sources and provides estimates for unavailable data, which are gauged against other data to verify for accuracy.

The I-O data obtained from IMPLAN are aggregated into seven basic industrial sectors: agriculture, mining, construction, manufacturing, utilities, professional services, and government services. These sectors are aggregated based on the North American Industry Classification System (NAICS) recognized by the United States Census Bureau [2]. Then, the agriculture sector is disaggregated into three sectors for more detailed analysis of agricultural activity: crop farming, animal husbandry, and other agricultural activities. Once this I-O data are incorporated into RCOT, the model is run for the 2012 base year to calculate the economic output associated with each of the industrial sectors. The output results produced by RCOT are then examined to verify that the model reproduces the sector output data provide by IMPLAN and ensure that this model accurately represents the Fauquier County economy. In scenarios where residential build-up is analyzed, a tenth sector is added to RCOT to represent the residential sector, which only distributes factors of production to final demand. Since the $y$ vector can be represented in mixed units, the total annual water demand associated with the local population is calculated based on the estimated demand reported by Hickey [3], 140 gal/capita/day, and this value is included as the final demand associated with the residential sector.

To build the $F^*$ matrix for Fauquier County's factor requirements per unit of output, six factors of production are identified as requirements for the economic sectors: labor, capital, land, water withdrawn, nitrogen applied as fertilizer produced outside of the county, and nitrogen applied as manure produced by the livestock in the animal husbandry sector. Sectoral data for labor, capital, and economic output, provided by IMPLAN, are used to calculate annual labor and capital requirements. Sectoral land requirements are determined using zoning data provided by the Fauquier County GIS Office [4] and land cover data obtained from the Virginia Geographic Information Network [5]. Water withdrawal requirements are determined for each industrial sector using data obtained from an I-O database compiled by the Green Design Institute at Carnegie Mellon University [6] and county water data available from the United States Geological Survey [7]. Agricultural nitrogen requirements are assumed based on county data available from the National Agricultural Statistics Service (NASS). Residential requirements for nitrogen as fertilizer are calculated based on application rates of fertilizer to lawns determined by Law, Band [8], specifically 27.8 kg N/ha of residential land/yr.


1. [datasets and Excel sheets] IMPLAN Group, LLC, *IMPLAN 2011-2013 Fauquier County Data*. 2016: Huntersville, NC. Available online: https://implan.com (accessed on 10 May 2021).
2. United States Census Bureau, *North American Industry Classification System*. 2017: United States. Available online: https://www.census.gov/naics/ (accessed on 10 May 2021).
3. Hickey, H.E., *Water Supply System Concepts*, in *Water Supply Systems and Evaluation Methods*. 2008, U.S Fire Administration.
4. [GIS shape files] Fauquier County GIS Office, *Fauquier County Zoning GIS Data*. 2014: Warrenton, VA. Available online: https://www.fauquiercounty.gov/government/departments-a-g/gis-mapping/gis-data (accessed on 10 May 2021).
5. [GIS shape files] Virginia Geographic Information Network, *Land cover dataset: Bay area 2*. 2016: United States. Available online: https://ftp.vgingis.com/download_2/land_cover/Bay_Area_2/ (accessed on 10 May 2021).

6. Blackhurst, M., C. Hendrickson, and J.S. Vidal, *Direct and indirect water withdrawals for U.S. industrial sectors*. Environmental Science & Technology, 2010. **44**(6): p. 2126-2130.
7. [Excel format] United States Geological Survey, *Estimated use of water in the United States county-level data for 2010*. 2010: United States. Available online: https://water.usgs.gov/watuse/data/2010/index.html (accessed on 10 May 2021).
8. Law, N., L. Band, and M. Grove, *Nitrogen input from residential lawn care practices in suburban watersheds in Baltimore county, MD*. Journal of Environmental Planning and Management, 2004. **47**(5): p. 737-755.

### B.1.1 Coefficient ($A^*$) Matrix

**Table B-1.** Coefficient ($A^*$) matrix used for Baseline of Chapter 3

| | Crop Farming | Animal Husbandry | Other Agricultural Activities | Mining | Construction | Manufacturing | Trade, Transportation Utilities | Professional Services | Government Services |
|---|---|---|---|---|---|---|---|---|---|
| **Crop Farming** | 0.0376 | 0.0001 | 0.0129 | 0.0001 | 0.0002 | 0.0029 | 0.0000 | 0.0000 | 0.0000 |
| **Animal Husbandry** | 0.0683 | 0.1058 | 0.0246 | 0.0001 | 0.0003 | 0.0055 | 0.0000 | 0.0000 | 0.0000 |
| **Other Agricultural Activities** | 0.0115 | 0.0115 | 0.0758 | 0.0001 | 0.0003 | 0.0054 | 0.0000 | 0.0000 | 0.0000 |
| **Mining** | 0.0009 | 0.0009 | 0.0009 | 0.0153 | 0.0058 | 0.0004 | 0.0030 | 0.0003 | 0.0006 |
| **Construction** | 0.0047 | 0.0047 | 0.0047 | 0.0516 | 0.0003 | 0.0031 | 0.0043 | 0.0170 | 0.0111 |
| **Manufacturing** | 0.0005 | 0.0005 | 0.0005 | 0.0001 | 0.0088 | 0.0019 | 0.0020 | 0.0012 | 0.0001 |
| **Trade, Transportation, Utilities** | 0.0432 | 0.0432 | 0.0432 | 0.0341 | 0.0789 | 0.0466 | 0.0418 | 0.0175 | 0.0016 |
| **Professional Services** | 0.0446 | 0.0446 | 0.0446 | 0.1088 | 0.0562 | 0.0622 | 0.1350 | 0.1723 | 0.0109 |
| **Government Services** | 0.0017 | 0.0017 | 0.0017 | 0.0008 | 0.0003 | 0.0017 | 0.0084 | 0.0021 | 0.0003 |

### B.1.2 Factor Requirement ($F^*$) Matrix

**Table B-2.** Factor Requirement ($F^*$) matrix used for Scenario 3 of Chapter 3

| | Crop Farming (/$M) | Animal Husbandry (/$M) | Other Agricultural Activities (/$M) | Mining (/$M) | Construction (/$M) | Manufacturing (/$M) | Trade, Transportation, Utilities (/$M) | Professional Services (/$M) | Government Services (/$M) | Residential Sector (/MG) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Labor (employees)** | 38.47 | 25.02 | 15.77 | 3.81 | 6.21 | 2.64 | 8.78 | 7.72 | 10.11 | 0.00 |
| **Capital ($M)** | 0.00 | 0.00 | 0.00 | 0.02 | 0.63 | 0.00 | 0.06 | 0.05 | 0.00 | 0.00 |
| **Land Use (ac)** | 1681.96 | 3758.17 | 1582.45 | 14.52 | 1.05 | 2.76 | 0.37 | 0.18 | 0.97 | 6.88 |
| **Water Withdrawal w/ Irrigation (MG)** | 508.00 | 19.50 | 0.00 | 2.68 | 0.37 | 10.46 | 0.16 | 0.18 | 1.33 | 1.10 |
| **$NO_3^-$ Applied as Fertilizer (short tons)** | 70.99 | 7.46 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.09 |
| **$NH_3$ Applied as Manure (short tons)** | 0.00 | 5.46 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

### B.1.5 Final Demand (y) Vector

**Table B-3.** Final Demand (y) vector used for Scenario 3 of Chapter 3

| | |
|---|---|
| **Crop Farming ($M)** | 25.67 |
| **Animal Husbandry ($M)** | 2.48 |
| **Other Agricultural Activities ($M)** | 2.94 |
| **Mining ($M)** | 9.65 |
| **Construction ($M)** | 0.00 |
| **Manufacturing ($M)** | 222.26 |
| **Trade, Transportation, Utilities ($M)** | 172.98 |
| **Professional Services ($M)** | 494.03 |
| **Government Services ($M)** | 266.98 |
| **Residential Sector (MG)** | 1288.29 |

### B.1.6 Factor Endowment (f) Vector

**Table B-4.** Factor Endowment (f) vector used for Scenario 4 of Chapter 3

| | |
|---|---|
| **Labor (employees)** | 36000 |
| **Capital ($M)** | 530 |
| **Land Use (ac)** | 94283 |
| **Water Withdrawal w/ Irrigation (MG)** | 14295 |
| **$NO_3^-$ Applied as Fertilizer (short tons)** | 1256 |
| **$NH_3$ Applied as Manure (short tons)** | 59 |

### B.1.7 Factor Price ($\pi$) Vector

**Table B-5.** Factor Price ($\pi$) vector used for Scenarios of Chapter 3

| | |
|---|---|
| **Wages ($/employee)** | 45,792 |
| **Payment to Capital ($/$M)** | 10,000 |
| **Land Rent ($/ac)** | 26 |
| **Water Billing Rate ($/MG)** | 60,072 |
| **Fertilizer Cost ($/short ton)** | 574 |
| **Manure Cost ($/short ton)** | 0 |

### B.1.8 Economic Output ($x^*$) Vector

**Table B-6.** Economic Output ($x^*$) vector obtained for Scenario 3 of Chapter 3

| | |
|---|---|
| **Crop Farming ($M)** | 27.98 |
| **Animal Husbandry ($M)** | 6.41 |
| **Other Agricultural Activities ($M)** | 4.95 |
| **Mining ($M)** | 10.98 |
| **Construction ($M)** | 16.47 |
| **Manufacturing ($M)** | 224.11 |
| **Trade, Transportation, Utilities ($M)** | 207.35 |
| **Professional Services ($M)** | 655.74 |
| **Government Services ($M)** | 270.62 |
| **Residential Sector (MG)** | 1288.29 |

### B.1.9 Factor Use (φ) Vector

**Table B-7.** Factor Use (φ) vector obtained for Scenario 3 of Chapter 3

| | |
|---|---|
| **Labor (employees)** | 11646 |
| **Capital ($M)** | 57.90 |
| **Land Use (ac)** | 88170.57 |
| **Water Withdrawal w/ Irrigation (MG)** | 18362.76 |
| **$NO_3^-$ Applied as Fertilizer (short tons)** | 2104.23 |
| **$NH_3$ Applied as Manure (short tons)** | 35.01 |

## B.2 Land Use Data Table

**Table B-8.** Land Use table in SCHEMATIC module for Scenario 3 of Chapter 3

| | | Pasture | Forest | Low Density Res. | Low Till. Corps | High Till. Corps | Industrial | Institutional | Medium Density Res. | Townhouse/ garden apt. | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **#** | **Segment** | **Land Use (Acre)** | | | | | | | | | **Sum** |
| | | **PERLND** | | | | | | | | | |
| **1** | **29** | 1009.8 | 0.0 | 1219.9 | 917.9 | 1194.2 | 13.4 | 6.5 | 9.1 | 2.2 | **4373.1** |
| **2** | **30** | 2524.0 | 0.0 | 1240.3 | 3954.1 | 3771.7 | 110.9 | 130.0 | 721.8 | 100.8 | **12553.6** |
| **3** | **34** | 12.2 | 430.7 | 254.6 | | | | | | | **697.5** |
| **4** | **35** | 994.3 | 4010.5 | 717.1 | 1271.4 | 481.5 | 10.3 | 103.3 | | | **7588.3** |
| **5** | **36** | 428.1 | 14775.7 | 855.7 | 710.4 | 9.1 | | 93.9 | | | **16872.8** |
| **6** | **37** | 1868.2 | 0.0 | 600.0 | 1725.8 | 1558.1 | 1.4 | 1.5 | 50.2 | | **5805.2** |
| **7** | **38** | 2409.2 | 0.0 | 624.8 | 3898.5 | 2908.2 | 183.2 | 73.1 | 82.8 | 15.0 | **10194.8** |
| **8** | **39** | 1553.9 | 0.0 | 166.4 | 1091.7 | 1013.3 | 37.5 | 14.9 | | | **3877.7** |
| **9** | **40** | 1586.8 | 0.0 | 304.1 | 2802.9 | 4023.6 | 57.7 | 7.9 | | | **8782.9** |
| **10** | **41** | 954.1 | 1561.0 | 386.3 | 3204.9 | 3404.8 | 19.6 | 40.3 | 13.0 | | **9583.9** |
| **11** | **42** | 315.0 | 1129.2 | 90.1 | 303.6 | 1450.8 | 4.5 | 2.3 | 1.4 | | **3296.9** |
| **12** | **43** | 349.8 | 1930.2 | 452.8 | 3052.0 | 6526.9 | | 7.4 | | | **12319.1** |
| **13** | **44** | 243.4 | 6885.9 | 425.4 | 197.2 | 1396.0 | 4.5 | 1.2 | | | **9153.5** |
| **14** | **47** | 199.7 | 2899.7 | 89.4 | 496.3 | 505.7 | 6.4 | 1.0 | | | **4198.2** |
| **15** | **55** | 2149.6 | 0.0 | 845.7 | 3768.3 | 3593.3 | 43.8 | 72.1 | 21.2 | | **10494.0** |
| **Sub-Total** | | **16598.1** | **33622.9** | **8272.5** | **27394.9** | **31837.0** | **493.1** | **555.5** | **899.5** | **118.1** | **119791.5** |
| | | **IMPLND** | | | | | | | | | |
| **1** | **29** | 1.9 | 25.5 | 135.5 | 1.3 | 7.0 | 13.4 | 3.5 | 2.3 | 1.2 | **191.6** |
| **2** | **30** | 17.2 | 75.9 | 137.8 | 12.5 | 8.7 | 110.9 | 70.0 | 180.4 | 54.3 | **667.7** |
| **3** | **34** | 0.1 | 4.4 | 28.3 | | | | | | | **32.8** |
| **4** | **35** | 10.0 | 40.5 | 79.7 | 25.9 | 9.8 | 10.3 | 55.6 | | | **232.0** |
| **5** | **36** | 4.3 | 149.2 | 95.1 | 14.5 | 0.2 | | 50.6 | | | **313.9** |
| **6** | **37** | 10.6 | 29.6 | 66.7 | 13.7 | 10.2 | 1.4 | 0.8 | 12.5 | | **145.6** |
| **7** | **38** | 16.0 | 54.1 | 69.4 | 33.3 | 13.0 | 183.2 | 39.3 | 20.7 | 8.1 | **437.2** |
| **8** | **39** | 7.4 | 17.3 | 18.5 | 13.2 | 11.6 | 37.5 | 8.0 | | | **113.5** |
| **9** | **40** | 7.7 | 41.7 | 33.8 | 23.5 | 48.4 | 57.7 | 4.3 | | | **217.0** |
| **10** | **41** | 9.6 | 59.8 | 42.9 | 20.9 | 25.0 | 19.6 | 21.7 | 3.2 | | **202.8** |
| **11** | **42** | 3.2 | 11.4 | 10.0 | 6.2 | 29.6 | 4.5 | 1.3 | 0.4 | | **66.5** |
| **12** | **43** | 3.5 | 63.5 | 50.3 | 17.8 | 88.7 | | 4.0 | | | **227.9** |
| **13** | **44** | 2.5 | 69.6 | 47.3 | 4.0 | 28.5 | 4.5 | 0.6 | | | **156.9** |
| **14** | **47** | 2.0 | 29.3 | 9.9 | 10.1 | 10.3 | 6.4 | 0.5 | | | **68.6** |
| **15** | **55** | 13.4 | 64.8 | 94.0 | 19.8 | 16.3 | 43.8 | 38.8 | 5.3 | | **296.2** |
| **Sub-Total** | | **109.5** | **109.5** | **736.6** | **919.2** | **216.7** | **307.4** | **493.1** | **299.1** | **224.9** | **3370.1** |
| **Total** | | **11277.5** | **16707.7** | **34359.5** | **9191.6** | **27611.6** | **32144.4** | **986.2** | **854.6** | **1124.3** | **123161.6** |

## B.3 Nitrogen Deposition Data Table

**Table B-9.** Nitrogen Deposition table in PQUAL module for Scenario 3 of Chapter 3

| | Jan | Feb | March | April | May | June | July | August | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pasture, $NH_3$ (lb/ac)** | 1.06E-01 | 1.06E-01 | 1.06E-01 | 1.06E-01 | 1.06E-01 | 1.06E-01 | 1.06E-01 | 1.06E-01 | 1.06E-01 | 1.06E-01 | 1.06E-01 | 1.06E-01 |
| **Pasture, $NO_3^-$ (lb/ac)** | 2.60E-04 | 2.60E-04 | 3.00E-04 | 3.00E-04 | 3.00E-04 | 1.90E-04 | 1.90E-04 | 1.74E+00 | 2.50E-04 | 2.50E-04 | 2.50E-04 | 2.60E-04 |
| **Low-Density Residential, $NO_3^-$ (lb/ac)** | 2.60E-04 | 2.60E-04 | 3.00E-04 | 3.00E-04 | 3.00E-04 | 1.90E-04 | 1.90E-04 | 1.90E-04 | 2.50E-04 | 2.50E-04 | 2.50E-04 | 2.60E-04 |
| **Cropland, $NO_3^-$ (lb/ac)** | 2.60E-04 | 2.60E-04 | 7.82E+01 | 3.00E-04 | 3.00E-04 | 1.90E-04 | 1.90E-04 | 1.90E-04 | 2.50E-04 | 2.50E-04 | 2.50E-04 | 2.60E-04 |

## B.4 Water Withdrawal Time Series

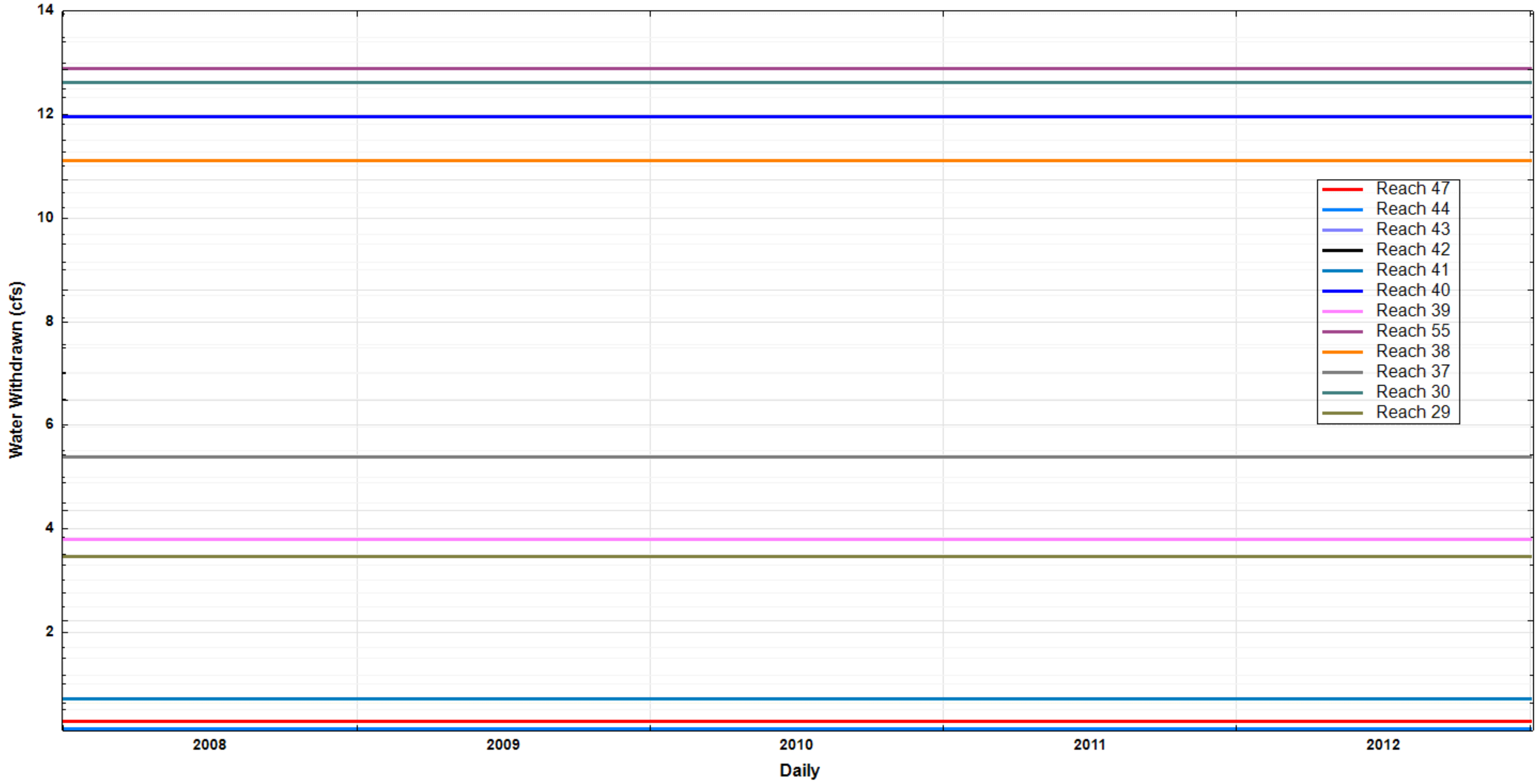


**Figure B-1.** Water Withdrawals input into HSPF as time series for Scenario 3 of Chapter 3

## B.5 Watershed Output Results

### B.5.1 Calculating Environmental Water Requirements

To determine the allowable quantity of water that can be extracted from the watershed without damaging the ecosystem, the environmental water requirements (EWR) were calculated for each channel reach following the process described by Smakhtin, Revenga, and Doll [1]. The total EWR is considered the combination of low-flow and high-flow requirements necessary to maintain the ecological health of each watershed segment. The low-flow requirement (LFR) for each segment is calculated by determining the monthly outflow that is exceeded 90% of the year ($Q_{90}$) under baseline conditions and aggregating that volume to the annual scale. The high-flow requirement (HFR) for each segment is calculated using Table B-10, adapted from [1], where MAR (mean annual runoff) refers to the average annual volume of total outflow from each segment in HSPF under baseline conditions. The sum of the LFR and HFR equates to the total EWR for each segment (see Table B-11). This value is then subtracted from the average annual volume of segment outflow to calculate the volume of water available for withdrawal during each scenario [1].

1. Smakhtin, V., C. Revenga, and P. Doll, *Taking into account environmental water requirements in global-scale water resources assessments*, in *Comprehensive assessment research report 2*. 2004: Colombo, Sri Lanka.

**Table B-10.** Guidelines to estimate environmental high-flow requirement

| Low-Flow Requirement ($Q_{90}$) | High-Flow Requirement (HFR) |
|---|---|
| *If* $Q_{90} < 10\%$ MAR | *Then* HFR = 20% MAR |
| *If* 10% MAR ≤ $Q_{90} < 20\%$ MAR | *Then* HFR = 15% MAR |
| *If* 20% MAR ≤ $Q_{90} < 30\%$ MAR | *Then* HFR = 7% MAR |
| *If* $Q_{90} \geq 30\%$ MAR | *Then* HFR = 0 |

**Table B-11.** Annual environmental water requirement (EWR) calculated for each segment ($ft^3/yr$)

| Segment | MAR ($ft^3/yr$) | LFR ($ft^3/yr$) | HFR ($ft^3/yr$) | EWR ($ft^3/yr$) |
|---|---|---|---|---|
| **29** | 170,264,622 | 14,165,107 | 34,052,924 | 48,218,032 |
| **30** | 688,270,071 | 95,698,231 | 103,240,511 | 198,938,742 |
| **37** | 1,070,479,019 | 150,258,943 | 160,571,853 | 310,830,796 |
| **38** | 441,300,372 | 43,637,340 | 66,195,056 | 109,832,396 |
| **55** | 434,659,793 | 34,839,527 | 86,931,959 | 121,771,486 |
| **39** | 1,674,134,004 | 257,494,772 | 251,120,101 | 508,614,873 |
| **40** | 787,740,574 | 60,139,093 | 157,548,115 | 217,687,208 |
| **41** | 2,968,228,723 | 393,085,104 | 445,234,308 | 838,319,413 |
| **42** | 1,134,986,319 | 114,946,626 | 170,247,948 | 285,194,574 |
| **43** | 489,970,087 | 29,399,670 | 97,994,017 | 127,393,687 |
| **44** | 475,426,404 | 38,008,861 | 95,085,281 | 133,094,142 |
| **47** | 4,320,234,892 | 525,567,848 | 648,035,234 | 1,173,603,082 |

### B.5.2 Water Outflow Volumes

Table B-12 displays the average annual volumes of segment outflow output from HSPF for Scenario 3 of Chapter 3. The first column displays the outflow volumes output from HSPF when water withdrawal was not input into the model. The second column displays the outflow volumes obtained from HSPF when water withdrawal was input into the model. The volume of water removed annually from each segment is displayed in the third column and is calculated by subtracting the volume in the second column from the volume in the first column. Finally, the fourth column displays the volume of water available for extraction from each segment, which was calculated by subtracting the EWR values described in Section B.5.1 from the outflow volumes displayed in the first column of the following tables.

**Table B-12.** Average annual volume of segment outflow obtained from HSPF for Scenario 3 of Chapter 3

| Segment | Outflow Volume w/o Withdrawal ($ft^3/yr$) | Outflow Volume w/ Withdrawal ($ft^3/yr$) | Water Removed ($ft^3/yr$) | Water Available for Removal ($ft^3/yr$) |
|---|---|---|---|---|
| **29** | 172,092,526 | 127,226,198 | 44,866,328 | 123,874,494 |
| **30** | 689,249,170 | 518,028,912 | 171,220,258 | 490,310,428 |
| **37** | 1,074,993,829 | 785,745,550 | 289,248,278 | 764,163,033 |
| **38** | 442,257,109 | 304,097,539 | 138,159,569 | 332,424,713 |
| **55** | 440,607,170 | 289,620,589 | 150,986,581 | 318,835,685 |
| **39** | 1,681,587,075 | 1,203,795,851 | 477,791,223 | 1,172,972,202 |
| **40** | 789,774,538 | 513,903,690 | 275,870,849 | 572,087,330 |
| **41** | 2,976,823,110 | 2,223,557,981 | 753,265,128 | 2,138,503,697 |
| **42** | 1,133,762,391 | 1,133,761,828 | 563 | 848,567,817 |
| **43** | 488,745,949 | 488,745,949 | 0 | 361,352,262 |
| **44** | 475,426,404 | 475,426,404 | 0 | 342,332,262 |
| **47** | 4,327,613,675 | 3,574,461,439 | 753,152,235 | 3,154,010,592 |

### B.5.3 Nitrogen Loadings

**Table B-13.** Average annual total nitrogen loading (kg/yr) in segment outflow obtained from HSPF for Scenarios of Chapter 3

| Segment | S1 | S2 | S3 | S4 |
|---|---|---|---|---|
| **29** | 4,683 | 4,975 | 4,107 | 2,638 |
| **30** | 36,957 | 39,326 | 77,890 | 11,053 |
| **37** | 58,428 | 62,301 | 102,950 | 17,944 |
| **38** | 15,459 | 16,066 | 16,078 | 12,303 |
| **55** | 14,639 | 16,601 | 15,811 | 28,624 |
| **39** | 94,002 | 109,100 | 145,575 | 76,052 |
| **40** | 27,099 | 28,155 | 32,033 | 25,198 |
| **41** | 180,222 | 182,596 | 407,876 | 209,995 |
| **42** | 18,265 | 18,265 | 18,074 | 17,956 |
| **43** | 7,836 | 7,836 | 7,643 | 7,524 |
| **44** | 6,894 | 6,894 | 6,894 | 6,894 |
| **47** | 209,475 | 212,804 | 426,605 | 226,516 |

## Appendix C

Appendix C provides example data tables representative of those used for scenario analysis in Chapter 4. These data tables include those input into and output from both RCOT and HSPF. The data are used in illustrative scenarios, which are developed to demonstrate the capabilities of the coupled modeling framework.

### C.1 Input-Output Data Tables

An economic database representative of Fauquier County had to be constructed for RCOT. To construct this database, sectoral economic data are obtained for the county representative of year 2012. This year serves as the base year because the most complete database that could be assembled for Fauquier County is representative of 2012. County-level, monetary, input-output data, and industry final demand data based on government data are obtained from a private company called IMPLAN Group, LLC (2016). IMPLAN obtains data from different sources and provides estimates for unavailable data, which are gauged against other data to ensure accuracy, to compile their I-O datasets.

The I-O data obtained from IMPLAN are aggregated into seven basic industrial sectors: agriculture, mining, construction, manufacturing, utilities, professional services, and government services. These sectors are aggregated using the North American Industry Classification System (NAICS), which is recognized by the United States Census Bureau (2017). For more detailed analysis of agricultural activity, the agriculture sector is then disaggregated into three sectors: crop farming, animal husbandry, and other agricultural activities. Once this data is input into RCOT, the model is run to calculate the economic output associated with each industrial sector for the 2012 base year. These output results are then assessed to ensure that the model reproduces the economic output data obtained from IMPLAN Group and to verify that this model is an accurate representation of the Fauquier County economy.

To build the factor requirement ($F^*$) matrix for RCOT, six factors of production are identified: labor, capital, land, water withdrawn, nitrogen applied as fertilizer produced outside of Fauquier County, and nitrogen applied as manure generated by the livestock associated with animal husbandry. Annual labor and capital requirements for each economic sector are calculated using sectoral data for labor, capital, and economic output obtained from IMPLAN. Sectoral land requirements are determined based on land cover data obtained from the Virginia Geographic Information Network (2016) and zoning data provided by the Fauquier County GIS Office (2014). Water withdrawal requirements for each industrial sector are determined using county water data provided by the United States Geological Survey (2010) and data obtained from an I-O database compiled by the Green Design Institute at Carnegie Mellon University (Blackhurst, Hendrickson, & Vidal, 2010). Agricultural nitrogen requirements are assumed based on data available for Fauquier County from the National Agricultural Statistics Service (NASS). In the scenarios where conjunctive use is introduced, excess nitrogen loading is included as a seventh factor of production to distinguish between the nine irrigation strategies that are introduced. Excess nitrogen loading is defined as the increase in nitrogen loading resulting from an increase in runoff caused by the addition of irrigation water. The quantity of excess nitrogen associated with each irrigation practice is determined by running HSPF under the different irrigation configurations and incorporating this information into RCOT.

The economic database constructed to represent Fauquier County is built using data available at the annual time scale. To run the economic model at the sub-annual time scale, the final demand (y) vector and the factor requirement ($F^*$) matrix had to be adjusted for each sub-annual timestep. Assuming the meteorological data collected between 2008 and 2012 are typical of the study region, average watershed outflow is higher during the first six months of a year (January through June) than during the second six months (July through December). Thus, in scenarios where a 6-month timestep is used, the first timestep is referred to as the wet season and the second timestep is referred to as the dry season. In scenarios where a 3-month timestep is used, the first timestep refers to January through March (Winter), the second timestep refers to April through June (Spring), the third timestep refers to July through September (Summer), and the fourth timestep refers to October through December (Fall). The seasons are assumed to correspond with these 3-month timesteps.

Because winter wheat and barley are listed as field crops in Fauquier County by NASS and in the report assembled by Rephann (2015), it is assumed that seasonal crop rotation is being practiced within the crop farming sector. As a result, when a 6-month timestep is used, it is assumed that the annual final demand associated with each economic sector is equally distributed among the wet and dry seasons of a year. 20% of the water annually required for agricultural activity is withdrawn during the wet season and the remaining 80% is withdrawn during the dry season to compensate for high evapotranspiration rates and lower channel outflow. It is assumed that the fertilizer required for the crop farming sector is applied during the wet season while fertilizer required for animal husbandry is applied during the dry season. When a 3-month timestep is used, it is assumed that the annual final demand associated with each economic sector is equally distributed among the four seasons in a year. It is assumed that 10% of the water annually required for agricultural activity is withdrawn during Winter, Spring, and Fall while the remaining 70% is withdrawn during Summer because average channel outflow is lowest during this season. It is also assumed that fertilizer required for crop farming is applied during Winter and that fertilizer required for animal husbandry is applied during Summer. Annual labor and land requirements are assumed to be constant throughout the seasons that make up the year.

Blackhurst, M., Hendrickson, C., & Vidal, J. S. (2010). Direct and indirect water withdrawals for U.S. industrial sectors. *Environmental Science & Technology, 44*(6), 2126-2130. doi:10.1021/es903147k

Fauquier County GIS Office. (2014). *Fauquier County Zoning GIS Data* [GIS shape files]. Warrenton, VA. Retrieved from: https://www.fauquiercounty.gov/government/departments-a-g/gis-mapping/gis-data (accessed May 10, 2021).

IMPLAN Group, LLC. (2016). *IMPLAN 2011-2013 Fauquier County Data* [Data sets and Excel sheets]. Retrieved from: https://implan.com (accessed May 10, 2021).

Rephann, T. J. (2015). *Fauquier County cost of community services study*. Weldon Cooper Center for Public Service, University of Virginia

United States Census Bureau. (2017). *North American Industry Classification System*. Retrieved from United States: https://www.census.gov/naics/ (accessed May 10, 2021).

United States Geological Survey. (2010). *Estimated use of water in the United States county-level data for 2010* [Excel format]. Retrieved from: https://water.usgs.gov/watuse/data/2010/index.html (accessed May 10, 2021).

Virginia Geographic Information Network. (2016). *Land cover dataset: Bay area 2* [GIS shape files]. Retrieved from: https://ftp.vgingis.com/download_2/land_cover/Bay_Area_2/ (accessed May 10, 2021).

### C.1.1 Coefficient ($A^*$) Matrix

**Table C-1.** Coefficient ($A^*$) matrix used for Scenario 1 of Chapter 4

| | Crop Farming | Animal Husbandry | Other Agricultural Activities | Mining | Construction | Manufacturing | Trade, Transportation Utilities | Professional Services | Government Services |
|---|---|---|---|---|---|---|---|---|---|
| **Crop Farming** | 0.0376 | 0.0001 | 0.0129 | 0.0001 | 0.0002 | 0.0029 | 0.0000 | 0.0000 | 0.0000 |
| **Animal Husbandry** | 0.0683 | 0.1058 | 0.0246 | 0.0001 | 0.0003 | 0.0055 | 0.0000 | 0.0000 | 0.0000 |
| **Other Agricultural Activities** | 0.0115 | 0.0115 | 0.0758 | 0.0001 | 0.0003 | 0.0054 | 0.0000 | 0.0000 | 0.0000 |
| **Mining** | 0.0009 | 0.0009 | 0.0009 | 0.0153 | 0.0058 | 0.0004 | 0.0030 | 0.0003 | 0.0006 |
| **Construction** | 0.0047 | 0.0047 | 0.0047 | 0.0516 | 0.0003 | 0.0031 | 0.0043 | 0.0170 | 0.0111 |
| **Manufacturing** | 0.0005 | 0.0005 | 0.0005 | 0.0001 | 0.0088 | 0.0019 | 0.0020 | 0.0012 | 0.0001 |
| **Trade, Transportation, Utilities** | 0.0432 | 0.0432 | 0.0432 | 0.0341 | 0.0789 | 0.0466 | 0.0418 | 0.0175 | 0.0016 |
| **Professional Services** | 0.0446 | 0.0446 | 0.0446 | 0.1088 | 0.0562 | 0.0622 | 0.1350 | 0.1723 | 0.0109 |
| **Government Services** | 0.0017 | 0.0017 | 0.0017 | 0.0008 | 0.0003 | 0.0017 | 0.0084 | 0.0021 | 0.0003 |

### C.1.2 Factor Requirement ($F^*$) Matrices

**Table C-2.** Factor Requirement ($F^*$) matrix used for wet season in Scenario 1 of Chapter 4

| | Crop Farming (/$M) | Animal Husbandry (/$M) | Other Agricultural Activities (/$M) | Mining (/$M) | Construction (/$M) | Manufacturing (/$M) | Trade, Transportation, Utilities (/$M) | Professional Services (/$M) | Government Services (/$M) |
|---|---|---|---|---|---|---|---|---|---|
| **Labor (employees)** | 76.94 | 50.03 | 31.55 | 7.62 | 12.42 | 5.28 | 17.57 | 15.43 | 20.21 |
| **Capital ($M)** | 0.00 | 0.00 | 0.00 | 0.02 | 0.63 | 0.00 | 0.06 | 0.05 | 0.00 |
| **Land Use (ac)** | 3363.92 | 7516.33 | 3164.90 | 29.04 | 2.11 | 5.52 | 0.75 | 0.35 | 1.94 |
| **Groundwater Withdrawal w/ Irrigation (MG)** | 203.20 | 9.48 | 0.00 | 2.68 | 0.37 | 10.46 | 0.16 | 0.18 | 1.33 |
| **$NO_3^-$ Applied as Fertilizer (short tons)** | 141.98 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **$NH_3$ Applied as Manure (short tons)** | 0.00 | 5.46 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Table C-3.** Factor Requirement ($F^*$) matrix used for dry season in Scenario 1 of Chapter 4

| | Crop Farming (/$M) | Animal Husbandry (/$M) | Other Agricultural Activities (/$M) | Mining (/$M) | Construction (/$M) | Manufacturing (/$M) | Trade, Transportation, Utilities (/$M) | Professional Services (/$M) | Government Services (/$M) |
|---|---|---|---|---|---|---|---|---|---|
| **Labor (employees)** | 76.94 | 50.03 | 31.55 | 7.62 | 12.42 | 5.28 | 17.57 | 15.43 | 20.21 |
| **Capital ($M)** | 0.00 | 0.00 | 0.00 | 0.02 | 0.63 | 0.00 | 0.06 | 0.05 | 0.00 |
| **Land Use (ac)** | 3363.92 | 7516.33 | 3164.90 | 29.04 | 2.11 | 5.52 | 0.75 | 0.35 | 1.94 |
| **Groundwater Withdrawal w/ Irrigation (MG)** | 812.80 | 9.48 | 0.00 | 2.68 | 0.37 | 10.46 | 0.16 | 0.18 | 1.33 |
| **$NO_3^-$ Applied as Fertilizer (short tons)** | 0.00 | 14.91 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **$NH_3$ Applied as Manure (short tons)** | 0.00 | 5.46 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

### C.1.5 Final Demand (y) Vector

**Table C-4.** Final Demand (y) vector used for Scenario 1 at bi-annual timestep of Chapter 4

| | |
|---|---|
| **Crop Farming ($M)** | 12.83 |
| **Animal Husbandry ($M)** | 1.24 |
| **Other Agricultural Activities ($M)** | 1.47 |
| **Mining ($M)** | 4.83 |
| **Construction ($M)** | 0.00 |
| **Manufacturing ($M)** | 111.13 |
| **Trade, Transportation, Utilities ($M)** | 86.49 |
| **Professional Services ($M)** | 247.02 |
| **Government Services ($M)** | 133.49 |

### C.1.6 Factor Endowment (f) Vector

**Table C-5.** Factor Endowment (f) vector used in final iteration for timesteps of Scenario 1 of Chapter 4

| | |
|---|---|
| **Labor (employees)** | 36000 |
| **Capital ($M)** | 530 |
| **Land Use (ac)** | 81465 |
| **Water Withdrawal w/ Irrigation (MG)** | 271924 |
| **$NO_3^-$ Applied as Fertilizer (short tons)** | 2000 |
| **$NH_3$ Applied as Manure (short tons)** | 59 |

### C.1.7 Factor Price (π) Vector

**Table C-6.** Factor Price (π) vector used for Scenario 1 of Chapter 4

| | |
|---|---|
| **Wages ($/employee)** | 22,896 |
| **Payment to Capital ($/$M)** | 10,000 |
| **Land Rent ($/ac)** | 13 |
| **Water Billing Rate ($/MG)** | 60,072 |
| **Fertilizer Cost ($/short ton)** | 574 |
| **Manure Cost ($/short ton)** | 0 |

### C.1.8 Economic Output ($x^*$) Vector

**Table C-7.** Economic Output ($x^*$) vector obtained at 6-month timestep for Scenario 1 of Chapter 4

| | |
|---|---|
| **Crop Farming ($M)** | 13.71 |
| **Animal Husbandry ($M)** | 3.21 |
| **Other Agricultural Activities ($M)** | 2.47 |
| **Mining ($M)** | 5.49 |
| **Construction ($M)** | 8.23 |
| **Manufacturing ($M)** | 112.06 |
| **Trade, Transportation, Utilities ($M)** | 103.67 |
| **Professional Services ($M)** | 327.87 |
| **Government Services ($M)** | 135.31 |

### C.1.9 Factor Use (ϕ) Vectors

**Table C-8.** Factor Use (ϕ) vector obtained for the wet season of Scenario 1 of Chapter 4

| | |
|---|---|
| **Labor (employees)** | 11645.94 |
| **Capital ($M)** | 28.95 |
| **Land Use (ac)** | 79307.10 |
| **Water Withdrawal w/ Irrigation (MG)** | 4261.88 |
| **$NO_3^-$ Applied as Fertilizer (short tons)** | 1946.48 |
| **$NH_3$ Applied as Manure (short tons)** | 17.51 |

**Table C-9.** Factor Use (ϕ) vector obtained for the dry season of Scenario 1 of Chapter 4

| | |
|---|---|
| **Labor (employees)** | 11645.94 |
| **Capital ($M)** | 28.95 |
| **Land Use (ac)** | 79307.10 |
| **Water Withdrawal w/ Irrigation (MG)** | 12619.50 |
| **$NO_3^-$ Applied as Fertilizer (short tons)** | 47.83 |
| **$NH_3$ Applied as Manure (short tons)** | 17.51 |

## C.2 Land Use Data Table

**Table C-10.** Land Use table in SCHEMATIC module for Scenarios of Chapter 4

| | | Pasture | Forest | Low Density Res. | Low Till. Corps | High Till. Corps | Industrial | Institutional | Medium Density Res. | Townhouse/ garden apt. | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **#** | **Segment** | **Land Use (Acre)** | | | | | | | | | **Sum** |
| **PERLND** | | | | | | | | | | | |
| **1** | **29** | 673.2 | 0.0 | 1219.9 | 1086.2 | 1362.5 | 13.4 | 6.5 | 9.1 | 2.2 | **4373.1** |
| **2** | **30** | 2187.4 | 3426.6 | 1240.3 | 2409.0 | 2226.6 | 110.9 | 130.0 | 721.8 | 100.8 | **12553.5** |
| **3** | **34** | 12.2 | 430.7 | 254.6 | | | | | | | **697.5** |
| **4** | **35** | 994.3 | 4010.5 | 717.1 | 1271.4 | 481.5 | 10.3 | 103.3 | | | **7588.3** |
| **5** | **36** | 428.1 | 14775.7 | 855.7 | 710.4 | 9.1 | | 93.9 | | | **16872.8** |
| **6** | **37** | 1531.7 | 0.0 | 600.0 | 1894.0 | 1726.4 | 1.4 | 1.5 | 50.2 | | **5805.2** |
| **7** | **38** | 2072.6 | 1276.9 | 624.8 | 3428.4 | 2438.1 | 183.2 | 73.1 | 82.8 | 15.0 | **10194.8** |
| **8** | **39** | 1217.3 | 0.0 | 166.4 | 1260.0 | 1181.7 | 37.5 | 14.9 | | | **3877.8** |
| **9** | **40** | 1250.2 | 42.3 | 304.1 | 2950.0 | 4170.8 | 57.7 | 7.9 | | | **8783.0** |
| **10** | **41** | 1439.3 | 1838.3 | 386.3 | 2823.7 | 3023.5 | 19.6 | 40.3 | 13.0 | | **9583.9** |
| **11** | **42** | 800.2 | 0.0 | 90.1 | 625.6 | 1772.7 | 4.5 | 2.3 | 1.4 | | **3297.0** |
| **12** | **43** | 835.1 | 2207.5 | 452.8 | 2670.7 | 6145.6 | | 7.4 | | | **12319.1** |
| **13** | **44** | 728.7 | 2803.1 | 425.4 | 1996.0 | 3194.7 | 4.5 | 1.2 | | | **9153.5** |
| **14** | **47** | 685.0 | 0.0 | 89.4 | 1703.5 | 1712.9 | 6.4 | 1.0 | | | **4198.1** |
| **15** | **55** | 1813.1 | 2330.7 | 845.7 | 2771.2 | 2596.2 | 43.8 | 72.1 | 21.2 | | **10494.0** |
| **Sub-Total** | | **16668.5** | **33142.2** | **8272.5** | **27600.1** | **32042.3** | **493.1** | **555.5** | **899.5** | **118.1** | **119791.6** |
| **IMPLND** | | | | | | | | | | | |
| **1** | **29** | 1.9 | 25.5 | 135.5 | 1.3 | 7.0 | 13.4 | 3.5 | 2.3 | 1.2 | **191.6** |
| **2** | **30** | 17.2 | 75.9 | 137.8 | 12.5 | 8.7 | 110.9 | 70.0 | 180.4 | 54.3 | **667.7** |
| **3** | **34** | 0.1 | 4.4 | 28.3 | | | | | | | **32.8** |
| **4** | **35** | 10.0 | 40.5 | 79.7 | 25.9 | 9.8 | 10.3 | 55.6 | | | **232.0** |
| **5** | **36** | 4.3 | 149.2 | 95.1 | 14.5 | 0.2 | | 50.6 | | | **313.9** |
| **6** | **37** | 10.6 | 29.6 | 66.7 | 13.7 | 10.2 | 1.4 | 0.8 | 12.5 | | **145.6** |
| **7** | **38** | 16.0 | 54.1 | 69.4 | 33.3 | 13.0 | 183.2 | 39.3 | 20.7 | 8.1 | **437.2** |
| **8** | **39** | 7.4 | 17.3 | 18.5 | 13.2 | 11.6 | 37.5 | 8.0 | | | **113.5** |
| **9** | **40** | 7.7 | 41.7 | 33.8 | 23.5 | 48.4 | 57.7 | 4.3 | | | **217.0** |
| **10** | **41** | 9.6 | 59.8 | 42.9 | 20.9 | 25.0 | 19.6 | 21.7 | 3.2 | | **202.8** |
| **11** | **42** | 3.2 | 11.4 | 10.0 | 6.2 | 29.6 | 4.5 | 1.3 | 0.4 | | **66.5** |
| **12** | **43** | 3.5 | 63.5 | 50.3 | 17.8 | 88.7 | | 4.0 | | | **227.9** |
| **13** | **44** | 2.5 | 69.6 | 47.3 | 4.0 | 28.5 | 4.5 | 0.6 | | | **156.9** |
| **14** | **47** | 2.0 | 29.3 | 9.9 | 10.1 | 10.3 | 6.4 | 0.5 | | | **68.6** |
| **15** | **55** | 13.4 | 64.8 | 94.0 | 19.8 | 16.3 | 43.8 | 38.8 | 5.3 | | **296.2** |
| **Sub-Total** | | **109.5** | **736.6** | **919.2** | **216.7** | **307.4** | **493.1** | **299.1** | **224.9** | **63.6** | **3370.1** |
| **Total** | | **16778.0** | **33878.8** | **9191.6** | **27816.8** | **32349.6** | **986.2** | **854.6** | **1124.3** | **181.6** | **123161.7** |

## C.3 Nitrogen Deposition Data Table

**Table C-11.** Nitrogen Deposition table in PQUAL module for Scenarios of Chapter 4

| | Jan | Feb | March | April | May | June | July | August | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pasture, $NH_3$ (lb/ac)** | 9.25E-02 | 9.25E-02 | 9.25E-02 | 9.25E-02 | 9.25E-02 | 9.25E-02 | 9.25E-02 | 9.25E-02 | 9.25E-02 | 9.25E-02 | 9.25E-02 | 9.25E-02 |
| **Pasture, $NO_3^-$ (lb/ac)** | 2.60E-04 | 2.60E-04 | 3.00E-04 | 3.00E-04 | 3.00E-04 | 1.90E-04 | 1.90E-04 | 1.52E+00 | 2.50E-04 | 2.50E-04 | 2.50E-04 | 2.60E-04 |
| **Cropland, $NO_3^-$ (lb/ac)** | 2.60E-04 | 2.60E-04 | 5.01E+01 | 3.00E-04 | 3.00E-04 | 1.90E-04 | 1.90E-04 | 1.90E-04 | 2.50E-04 | 2.50E-04 | 2.50E-04 | 2.60E-04 |

## C.4 Irrigation Demand Time Series

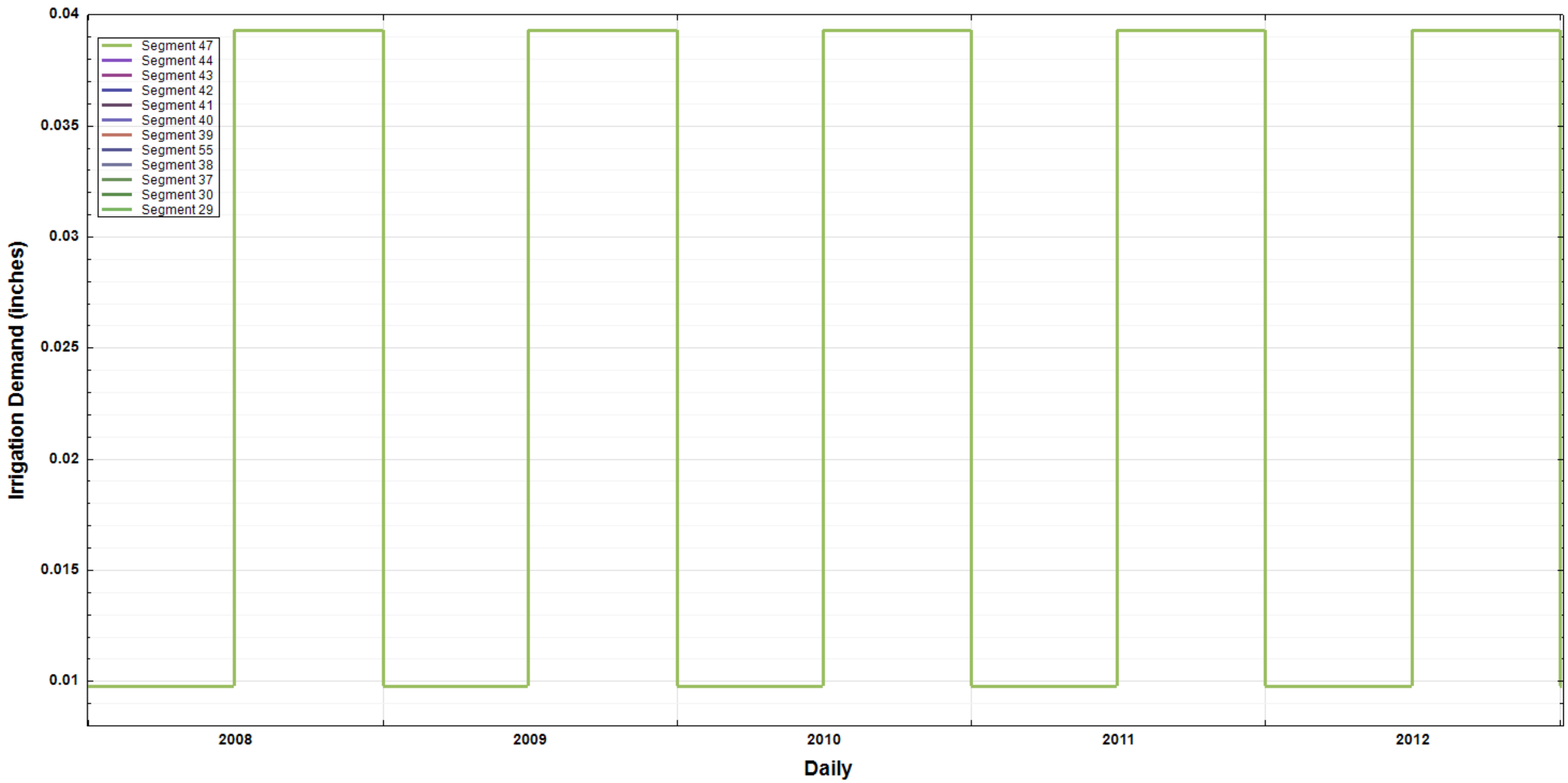


**Figure C-1.** Irrigation Demand input into HSPF as time series for Scenario 1 of Chapter 4

## C.5 Watershed Output Results

### C.5.1 Water Outflow Volumes

**Table C-12.** Total outflow from Segment 47 (MG/timestep) for Scenario 1 of Chapter 4

| Year | | 1 | 2 | 3 | 4 | 5 | Average |
|---|---|---|---|---|---|---|---|
| Timestep | Wet | 19,431 | 18,525 | 14,364 | 22,532 | 14,094 | 17,789 |
| | Dry | 5,202 | 14,841 | 6,018 | 20,320 | 7,465 | 10,769 |

### C.5.2 Nitrogen Loadings

**Table C-13.** Total nitrogen loading from Segment 47 (kg/timestep) for Scenario 1 of Chapter 4

| Year | | 1 | 2 | 3 | 4 | 5 | Average |
|---|---|---|---|---|---|---|---|
| Timestep | Wet | 293,723 | 307,378 | 1,166,318 | 4,399,743 | 1,180,149 | 1,469,462 |
| | Dry | 14,064 | 45,844 | 14,014 | 59,617 | 18,371 | 30,382 |