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Applying a Coupled Hydrologic-Economic Modeling Framework: Evaluating Alternative Options for Reducing Impacts for Downstream Locations in Response to Upstream Development

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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. 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 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

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1. 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) databases have 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 analysis 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. The World Trade Model (WTM), an inter-regional trade I-O model based on the theory of comparative advantage developed by Duchin [6], was first used for global analysis [7,8], but it has also been applied to contiguous regions. For example, Dilekli and Duchin [9] applied WTM 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 [10]. 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 [11]. 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 [12] to evaluate water withdrawal policies and their economic implications for thirteen hydro-economic regions in Mexico. Lutter, Pfister [13] 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 [2,14]. 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.

1.1. 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 20th 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 [15,16].

Located within Fauquier County is Cedar Run Watershed (498 km^2), a sub-basin of Occoquan Watershed (1515 km^2) located 50 km southwest of Washington DC. Based on local precipitation data collected from 2008 to 2012, Cedar Run Watershed receives an average of about 41 inches of rain per year. 64% of this annual precipitation is lost to the watershed system due to evapotranspiration [17]. 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 [18]. 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 [19]. 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.

1.2. 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 [20], 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 [21]. 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 [22]. 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 [23,24]. This same calibrated model is used in this application of the hydrologic-economic modeling framework. 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?

2. Materials and Methods

2.1. 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 [25] 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 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.

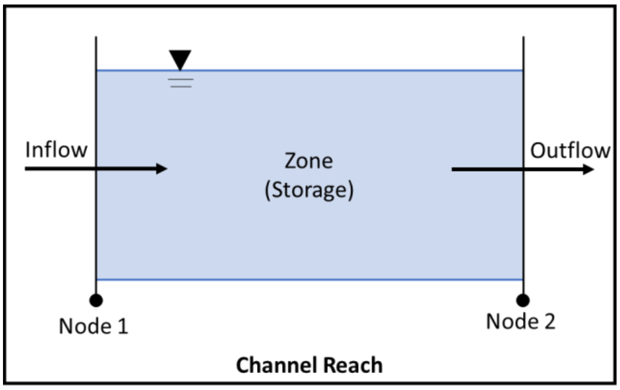

Figure 1. The zones and nodes that compose the element type called Channel Reach. Note: ▼ refers to water level.

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 [25]:

$$\frac{d}{dt}V = V_{in} - V_{out} + P - E - W \tag{1}$$

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 [25]:

$$\frac{d}{dt}N = N_{in} - D - [N_{OL} + N_{SED} + N_{I} + N_{GW}] \tag{2}$$

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 [25].

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 2.

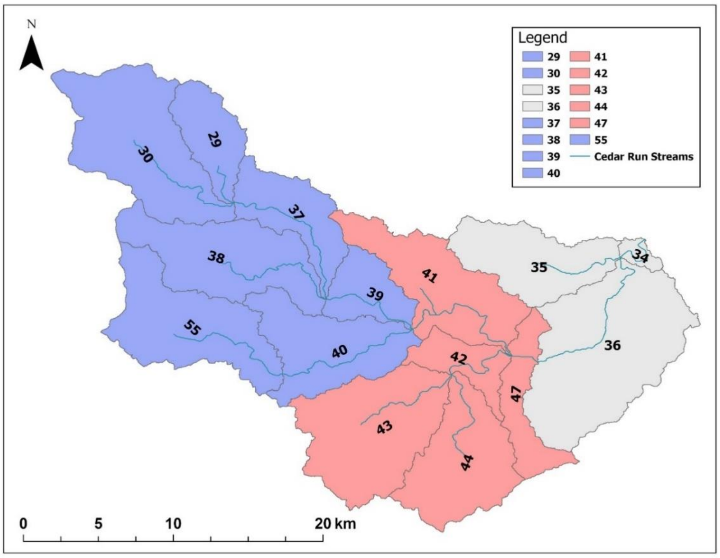

Figure 2. Cedar Run Watershed divided into numbered segments, including Upstream (blue), Downstream (red), and Segments 34, 35, and 36, which lie outside of Fauquier County (gray). Note: Adapted with permission from [20]. 2021, Amaya et al.

2.2. 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 [21]. 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 [26] and nitrogen [27]. 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 [21] 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):

$$(\mathrm{I}^* - \mathrm{A}^*)\mathrm{x}^* = \mathrm{y} \ \rightarrow \ \mathbf{x}^* = (\mathbf{I}^* - \mathbf{A}^*)^{-1}\,\mathbf{y} \tag{3}$$

$$\varphi = \mathrm{F}^*\mathrm{x}^* \rightarrow \ \boldsymbol{\varphi} = \mathbf{F}^*(\mathbf{I}^* - \mathbf{A}^*)^{-1}\mathbf{y} \tag{4}$$

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

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:

$$\text{Minimize } \boldsymbol{M} = \boldsymbol{\pi}'\mathbf{F}^*\mathbf{x}^* \tag{5}$$

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

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

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

$$\mathbf{p} = \left(\mathbf{I}^* - \mathbf{A}^{*\prime}\right)^{-1}\mathbf{F}^{*\prime}\boldsymbol{\pi} \tag{6}$$

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

$$\text{Maximize } \boldsymbol{W} = \mathbf{p}'\mathbf{y} - \mathbf{r}'\mathbf{f} \tag{7}$$

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

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

At the optimal solution, the two objective functions displayed in Equations (5) and (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 [21].

2.3. 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 (Huntersville, NC, USA) [28]. 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 [29], 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 [30]. Then, the agriculture sector is disaggregated into three sectors for more detailed analysis of agricultural activity as was done by Julia and Duchin [7]: 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 [31], 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 [32] and land cover data obtained from the Virginia Geographic Information Network [33]. 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 [34] and county water data available from the United States Geological Survey [35]. 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 [36], specifically 27.8 kg N/ha of residential land/yr.

2.4. Model Calibration and Validation

As previously mentioned, the HSPF model utilized in this study was calibrated to represent Cedar Run Watershed by OWML using data collected from 2008 to 2012. The process utilized by OWML to calibrate this established watershed model is described in detail in [18,23], but will be briefly summarized in this sub-section. To model hydrological behavior, meteorological data are input into HSPF as a time series. Air temperature, cloud cover, dew point temperature, wind speed, and solar radiation are collected at an hourly timestep from the regional weather station (Dulles station) while potential evapotranspiration is estimated using the Penman Pan empirical method. Precipitation data, collected at the rain gauge station located in Cedar Run Watershed, are also input into HSPF at the hourly timestep. The watershed model is calibrated by comparing model results, output at the daily timestep, with observed data collected at the stream monitoring station from 2008 to 2010. The model is then validated using observed data collected at the monitoring station from 2011 to 2012. This observed data includes both daily and monthly streamflow as well as water quality constituents, such as monthly loadings of total suspended solids (TSS), phosphorus, ammonium, and nitrate. Seven principal hydrologic parameters are adjusted in the rainfall-runoff calibration process for HSPF (defined in [25]):

- Groundwater recession rate (AGWRC)
- Interflow recession rate (IRC)
- Index to soil infiltration capacity (INFILT)
- Index to lower zone evapotranspiration (LZETP)
- Lower zone soil moisture storage (LZSN)
- Upper zone soil moisture storage (UZSN)
- Interflow inflow parameter (INTFW)

The calibrated values for these parameters lie within the recommended ranges except for IRC, which lies slightly below the typical range but still within acceptable limits. Several statistical methods are used to evaluate calibration/validation performance, including the standard coefficient of determination (R^2) used to evaluate daily and monthly flow results as well as the Nash-Sutcliffe Efficiency (NSE) coefficient used to evaluate monthly TSS, phosphorus, and nitrogen loadings [37]. These error statistics result in values of 0.76 for daily flow (good), 0.83 for monthly flow (very good), 0.62 for TSS loading (satisfactory), 0.79 for phosphorus loading (very good), 0.76 for ammonium loading (very good), and 0.80 for nitrate loading (very good). Thus, the HSPF model has been calibrated successfully and adequately represents Cedar Run Watershed.

Because HSPF and RCOT were created by researchers in different disciplines to represent different types of systems, the processes utilized to ensure that the databases required by each model to adequately represent their respective system are also different. All the parameters required for the RCOT database are based on accounting data compiled by statistical offices based on data compiled by government agencies for specific past years. I-O transaction data and economic output data obtained from IMPLAN are used to calculate the values that populate the coefficient (A^*) matrix utilized by the model to represent Fauquier County. When using the final demand data provided for the base year, the output results generated by RCOT are the same values as the sector output data obtained from IMPLAN [28] because all the data necessary to calculate economic output are provided by this company (see Equation (3)). The sectoral data provided by IMPLAN are also detailed enough that when the agricultural sector is disaggregated into three sectors, the coefficients associated with these additional sectors are easily determined in the A^* matrix. As a result, the economic output results produced by RCOT match the provided economic output data for these disaggregated sectors. Thus, while the calibration process for HSPF involves adjusting seven principal parameters so that the results output from the watershed model are within acceptable range of data observed in Cedar Run Watershed, very little parameter adjustment is required to represent the economy of Fauquier County in RCOT.

2.5. Coupled Modular Framework

The coupled modeling framework utilized in this study is described in [20], 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 [38,39]. 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 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 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. 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.

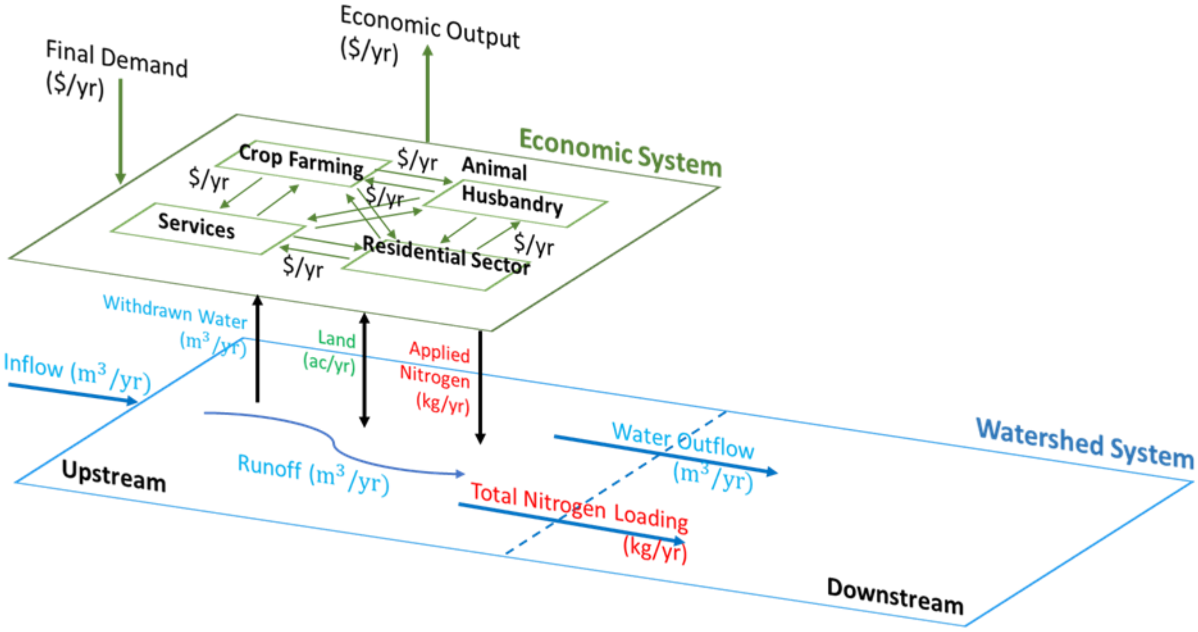

Figure 3. New economic activity lies in the upstream region and affects downstream watershed health. Note: **green arrows** refer to consumption and production flows within the economic system, **blue arrows** refer to flow of constituents through the watershed system, and **black arrows** refer to interactions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

Table 1. Scenario characteristics.

Scenario Name	S1	S2	S3	S4
Scenario Description	Upstream Residential Build-Up	Upstream Residential Build-Up	Upstream Agricultural Intensification	Upstream Agricultural Intensification
New Technologies 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

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 (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 (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 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.

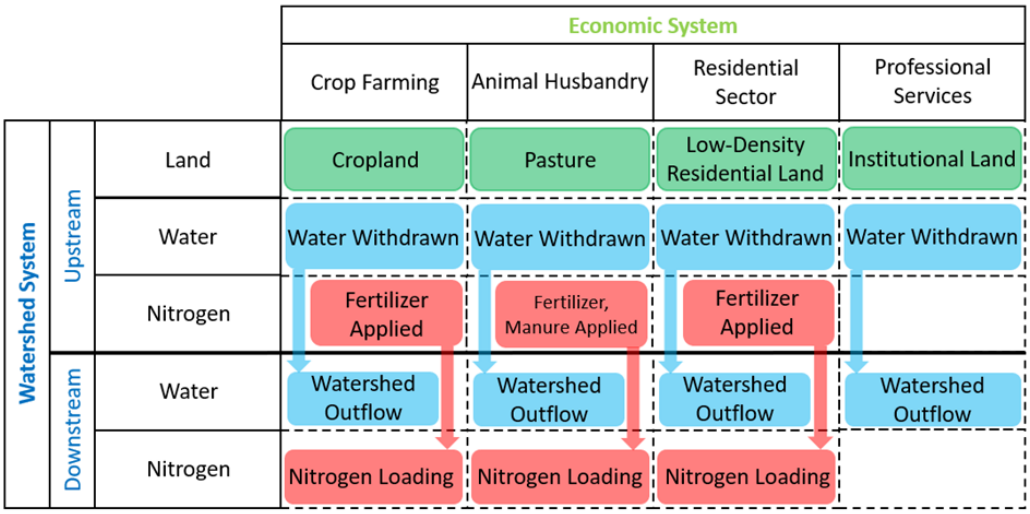

Figure 4. Factors of production (land, water, nitrogen) are utilized by economic sectors in the upstream region and affect downstream watershed outflow and nitrogen loading.

3. Scenarios

An economic database is constructed to represent Fauquier County using input-output data from 2012 (see Section 2.3). Additionally, local monitoring data were collected from 2008 to 2012 by OWML to calibrate and validate an HSPF model to represent Cedar Run Watershed [37]. Utilizing this data in the coupled hydrologic-economic framework described in Section 2, 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 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 [40]. 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 [40]. 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.

3.1. Residential Build-Up (S1 & S2)

Under Scenarios 1 and 2 (referred to as S1 and S2 in Table 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 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 [41]: 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 [41]. 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 [41]. 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

3.2. *Agricultural Intensification (S3 & S4)*

Under Scenarios 3 and 4 (referred to as S3 and S4 in Table 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 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 [18], 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

4. Results

As mentioned in the previous section, the scenarios developed in this study are illustrative and intended to demonstrate the capabilities of the coupled modeling framework. These scenarios are also designed to examine future development prospects. Since HSPF and RCOT are both deterministic models, the results produced by these scenarios cannot be interpreted as predictions but rather as insights into the interactions between human (economic) and natural (watershed) systems, specifically the impacts of change caused by the availability of different technologies in the future. Scenario results are compared to noted trends in Fauquier County to determine if the results make sense for the region of study.

Scenario results include those produced by the factor use (φ) vector of the economic model (see Table 2), which are obtained using a version of the RCOT model programmed using LINGO software [42]. 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. Although two or more technologies may be used simultaneously, RCOT does not select Rainwater Harvesting under S2 and so this technology does not contribute to the difference in water withdrawal associated with this scenario when compared to S1.

Table 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

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. Specifically, 97% of economic output from the crop farming sector is associated with Vegetable & Fruit Farming while the remaining 3.0% is associated with the implementation of Reclamation Water. As a result, while cropland increases by 270% under S3, the cropland reduces by 58% under S4 as shown in Table 2.

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) and the average annual total nitrogen concentration present in the outflow from each of these segments (see Table 4). 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. 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

Table 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

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.

5. 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 [16]. This shift from cereals to other more high-value crops is also observed in a scenario analysis conducted by Springer and Duchin [8] 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 [11,43]. However, RCOT's unique features allow for technological 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 [20]. RCOT possesses these features because the theory of comparative advantage, a global trade theory, is incorporated into the logic of this model. First embodied in the World Trade Model (WTM), this theory indicates that a region will utilize the most efficient technology available to meet final demand until some required resource becomes scarce. At that point, the next most efficient technology that is less intensive in the scarce resource will be utilized even though it is less efficient than the first choice [6].

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 [44]. 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.

5.1. 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. If the technology or management practice selected to satisfy final demand is the most efficient of the alternatives considered, then the most efficient solution is also the least costly solution. If resource constraints prevent the lowest cost technology from satisfying full demand, then the next most efficient technology is also selected. 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.

5.2. 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 [45], 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 [46–49].

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scenarios with the support of F.D., E.H. and J.C.L., who all provided substantial input. M.A. drafted the manuscript and designed the figures with feedback and revisions provided by F.D., E.H. and J.C.L. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. Most of the raw data used to build the economic database for Fauquier County are publicly available datasets (see References for links). Restrictions apply to the availability of the county-level sectoral data used to build the economic database. These data were obtained from IMPLAN Group, LLC and are available at www.implan.com (accessed on 9 May 2019) with IMPLAN's permission. Restrictions also apply to the availability of the data used to calibrate the watershed model for Cedar Run Watershed. These data were obtained from Occoquan Watershed Monitoring Laboratory (OWML) and are available from the authors with the permission of OWML.

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