WEB-BASED MULTI-CRITERIA EVALUATION OF SPATIAL TRADE-OFFS BETWEEN ENVIRONMENTAL AND ECONOMIC IMPLICATION FROM HYDRAULIC FRACTURING IN A SHALE GAS REGION IN OHIO

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ABSTRACT

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Planning of shale gas infrastructure and drilling sites for hydraulic fracturing has important spatial implications. The evaluation of conflicting and competing objectives requires an explicit consideration of multiple criteria as they have important environmental and economic implications. This study presents a web-based multi-criteria spatial decision support system (SDSS) prototype with a flexible and user-friendly interface that could provide educational or decision-making capabilities with respect to hydraulic fracturing site-selection in eastern Ohio. One of the main features of this spatial decision support system is to emphasize potential trade-offs between important factors of environmental and economic implications from hydraulic fracturing activities using a weighted linear combination (WLC) method. WLC is a simple approach that integrates users' preferences into an overall assessment and offers a rationale for trade-offs between decision criteria and objectives. In the prototype, the GIS-enabled analytical components allow spontaneous visualization of available alternatives on maps which provide value-added features for decision support processes and derivation of final decision maps. The SDSS prototype exhibits a straightforward decision-making procedure with easy-to-use web interface and facilitates non-expert participation capabilities. It comprises of a mapping module, decision-making tool, group decision data statistics, and social media sharing tools. The system architecture combines a variety of closely related components using Silverlight, ArcGIS API for Silverlight, ArcGIS Server, and ArcSDE for SQL Server software. During the decision-making process, users are

guided through a logical flow of successively presented forms and standardized criteria maps to generate visualization of trade-off scenarios and alternative solutions tailored to their personal preferences. Finally, the results and the preferences from all users are graphed for visualization and subsequent decision-making making.

This is dedicated to my family and friends. Thank you all for your endless love and support throughout my life.

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1. INTRODUCTION

Natural gas extracted from dense shale rock formations has become the fastest-growing source of energy in the United States and could represent a significant new global source of energy. The process of shale gas extraction is called hydraulic fracturing or “fracking,” which involves the propagation of fractures in deep rock formations by injecting pressurized fluid consisting of water, chemicals, and sand. This process forces the shale rock to break apart and release the oil or natural gas that cannot be extracted by other conventional drilling techniques (GWPC, 2009; U.S. EPA, 2004; IOGCC, 2002).

In the U.S., shale gas resources cover large contiguous areas at varying depths between 300 and 4,500 m. The U.S. has more than 2,500 trillion cubic feet (TCF) of technically recoverable natural gas resources, of which 33 percent is held in shale rock formations (EIA, 2012). The five largest shale gas formations in the U.S. are the Marcellus, Haynesville, Barnett, Woodford, and Fayetteville. In those formations, the U.S. Energy Information Administration estimations show varying amounts of technically recoverable natural gas resources from 84 TCF for the Marcellus to 5 TCF for the Fayetteville. Other expectations are that the industry will create many direct and supply chain jobs as well as other economic development benefits (USGS, 2012; EIA, 2011; Hefley et al, 2011).

Natural gas extraction from unconventional sources such as shale rock formations is a complex and costly process that requires a combination of new technological advances for directional drilling (i.e., non-vertical or horizontal drilling) and hydraulic fracturing for increased productivity of economically viable natural gas. Those new technologies for unconventional gas drilling are emerging as one of the most controversial issues, as people have raised concerns about the adverse environmental and social implications of drilling practices, especially related to impacts on water resources (Buckingham, 2011; Kargbo, et al., 2010). For example, the Ohio Environmental Protection Agency (Ohio EPA, 2013) estimates that hydraulic fracturing for a typical well requires 2 to 6 million gallons of pressurized fluid to fracture the shale. Fifteen to twenty percent of the fluid flows back to the surface, cannot be treated and must be disposed. Under those circumstances, the large amount of polluted water can pose a great threat to the local water resources. In addition, hydraulic fracturing affects the natural recharge of aquifers, which is a gravity driven process that is influenced by the permeability of the strata between the source of the recharge and the aquifer (Jenner and Lamadrid, 2012; Arthur et al., 2008; Hayes, 2009; Soeder and Kappel, 2009; U.S. EPA, 2004).

Other consequences from a typical shale gas drilling site include the direct visual impacts across the landscape and upon its inhabitants through its indelible infrastructural footprint in the midst of forests, open spaces, rural areas, agricultural fields and public lands (Steiner, 2012). For example, a survey undertaken by Penn State Public Broadcasting (PSPB, 2013) suggests that typical construction of a pad site occupies from five to eight acres of land, which are allocated for water impoundments, construction of transportation systems, and other facilities. As a result, the direct visual impact on the current landscape in Pennsylvania is estimated to be 20,800 acres (0.07% of total area). Other potential effects from hydraulic fracturing to the environment and communities stem from air pollution, soil and groundwater contamination, water use and waste water management, radioactive contamination, noise and traffic activities as well as possible small scale seismic activities. Because of the above concerns, hydraulic fracturing is facing mounting opposition across the country, with moratoriums even being declared in several states such as New Jersey and New York (Hall, 2011; Pool, 2011; Rahm, 2011). On the other hand, proponents consider this new technology as a way of reducing the country's dependence on foreign oil and gas, lowering the carbon footprint compared to using coal, as well as providing direct economic stimulus to the local and the state economies (Rahm et al., 2013).

Solving complex problems with conflicting issues, such as environmental impact versus economic prosperity from hydraulic fracturing, requires collaboration between general public and private interest for understanding the trade-offs and severity of the conflict before policies and decision-making capabilities are formulated and implemented. Some attempts aimed to resolve controversies and to enhance decision-making processes have used the assistance of a spatial decision support system (SDSS). SDSS is an interactive computer-based system for decision making processes that involves the integration of Geographic Information Systems (GIS) with the analytical capabilities of multiple criteria evaluation (MCE). GIS is capable of manipulating, categorizing, and displaying diverse spatial information as well as proposing location alternatives through flexible problem-solving tools and strategies (Gorsevski, 2013; Zhang et al., 2011; Boroushaki and Malczewski, 2010a; Chakroun and Benie, 2005; Power, 2002). Thus, implementation of GIS provides a powerful platform that can enhance the public and private participation and assist in solving complex spatial decision problems (Roger and Cottrell, 2012). Nevertheless, GIS alone is insufficient to solve spatial problems affected by complex societal issues, without the assistance of MCE, which provides the mechanism for solving the problems through integrated user participation, education and a computer interface.

Therefore, the usefulness of MCE within the SDSS framework is that it combines a set of criteria that are aimed to achieve a single score composite for decision making purposes according to a specific objective. For instance, criteria that represent suitable or unsuitable drilling locations are combined by methods such as Boolean or weighted linear combination (WLC) procedures to support an objective that is used for decision making (Donevska et al., 2012; Drobne and Lisec, 2009). Unlike the Boolean procedure, where the result from the aggregated criteria carries the lowest possible risk because suitable or unsuitable areas must include all criteria, the WLC is characterized by trade-offs between criteria and objectives. The weights in the WLC determine the level of trade-off where higher criterion weights have more influence on the final solution and can be used to explore different decision outcomes of complex problems. Some applications that take advantage of those frameworks include wind farm site selection (Aydin et al., 2010; Berry et al., 2011; Gorsevski et al., 2013; Grassi et al., 2012; Simão et al., 2009; Van et al. , 2011), landfill site selection (Gorsevski et al., 2012; Donevska et al., 2012), watershed management (Zhang et al., 2011; Choi et al., 2005;), risk-based management (Purucker et al, 2009), and natural hazard risk assessment (Stewart et al., 2014; Alcorn et al., 2013; Chen et al., 2013; Gorsevski et al., 2006; Ayalew et al., 2004).

The wide use of the internet and the increasing demand for the public to participate in policy decision-making has spurred the emergence of web-based SDSS (Damos & Karabatakis, 2013; Joseph-Williams et al, 2013; Alonso et al., 2010). The web-based frameworks allow users to articulate their voices and preferences through user-friendly decision-making tools without being restricted by time and place (Boroushaki and Malczewski, 2010a; Simao et al., 2009; Jankowski and Stasik, 1997). Jankowski and Nyerges (2003) emphasize that successful public participation for decision-making purposes requires not only powerful hardware and software, but also feasible forms of participation that satisfy the need for efficient and judicial communication and subsequent consensus building (Taranu, 2009). With the SDSS accessible to the general public, citizens will be able to express their local knowledge and preferences to contribute to the spatial planning process, which has previously been dominated by experts and other high level decision makers (Simao et al., 2009). In addition the implementation of this framework makes the public planning process more transparent. For instance, Michanowicz et al. (2010) proposed a knowledge enhancement tool that intended to stimulate capacity building in local community planning called "FracTracker". FracTracker takes advantage of the GIS and public participation and allows non-expert participation through different web based modules such as exchange of drilling experiences, interoperability of geospatial data, and visualization of maps and charts associated with drilling locations. The main goal of this tool is to understand and communicate challenges associated with the natural gas extraction for the Marcellus shale gas industry. However, FracTracker is not intended for web-based spatial decision making and planning and it lacks spatial decision support capabilities.

The objective of this project is to present a custom-built web-based SDSS intended for site suitability analysis of hydraulic fracturing that can strengthen public involvement and increase public awareness of environmental and economic planning consequences. The prototype system intends to facilitate public involvement in an easily-accessible, flexible, and customizable environment using easy-to-use web-based graphic user interfaces (GUI). In particular, in this preliminary state of the development the aim of the tool is to involve expert and non-expert participants that can explore different planning scenarios using conflicting objectives. However, because of the complexity with the issue of hydraulic fracturing, the intent of the proposed prototype tool is to initiate ideas for future compromised solutions for land allocation through spatial visualization and trade-offs between the competing objectives and educating the community about environmental and economic implications of hydraulic fracturing.

2. STUDY AREA AND DATASET

2.1 Study Area

The study area is located in eastern Ohio (Fig.1), which is defined here by the western limit of the Marcellus Shale to the west and the state boundary of Ohio to the east. According to USGS (2010), the Marcellus Shale gas play within Ohio accounts for 18.2 % of the total natural gas located in the Appalachian Basin. The Marcellus Shale play which comprises mainly dry natural gas, has a thickness between 0 m and 27 m and lies more than 2,000 m below the surface (Romich and Schumacher, 2012). The Marcellus Shale located in West Virginia and Pennsylvania has already extensively been leased by gas companies, while Ohio has not undergone large-scale exploitation. The reason for smaller scale gas exploitation in Ohio is due to different state policies and a late start of hydraulic fracturing in 1940s (EIA, 2011; Engelder and Lash, 2008). However, it is estimated that more than 80,000 wells in Ohio have already been drilled through hydraulic fracturing with most of the wells located in eastern Ohio. Meanwhile, pipelines of around 72,000 miles across the state of Ohio have been built for both long-distance transmission and short-range delivery.

A stable and abundant water supply is a crucial prerequisite for hydraulic fracturing. Ohio has an abundance of fresh water sources from both surface and underground supplies. Considering the 30 trillion gallons of annual precipitation which more than adequately recharges local streams, rivers, lakes and aquifers, Ohio has sufficient water supply to facilitate the Marcellus Shale gas drilling (Ohio EPA, 2013). In spite of the abundant water supply, protection of both surface water and groundwater during drilling processes deserves more attention. Ohio Department of Natural Resources (ODNR, 2013)'s Division of Oil and Gas Resources Management has been applying tight requirements towards oil and gas well permits. For example some of the well casing requirements intend to isolate and prevent potential contamination during the drilling processes. Furthermore, ODNR have been working on water management to ensure the availability of water for all purposes via withdrawal registration and water usage monitoring, as well as reporting. This tight policy and management system serves as effective supervision and control for water management in hydraulic fracturing industry.

2.2 Evaluation Criteria

Figure 2 shows the hierarchical structure of the decision process for evaluation of multiple environmental and economic considerations. The hierarchical organization of the constraints and criteria has four levels, including the goal, constraints, objectives, and factors. The top level represents the goal of the decision hierarchy to identify the least controversial locations for hydraulic fracturing. The next level excludes hydraulic fracturing within parts of the study area, based on legal restrictions or physical limitations. In this hierarchical level, protected zones such as national parks, wetlands, and urban areas or populated places are excluded from the analysis. The third level demonstrates the multi-objective multi-criteria considerations which are aimed to address two important societal issues including: environmental and economic concerns with hydraulic fracturing. The environmental objective considers the distance of fracking locations from the following criteria: wildlife habitats, rivers, lakes, faults, and urban areas. The economic objective considers the following criteria: proximity to roads, proximity to pipelines, and proximity to storage areas, Marcellus Shale thickness, and population density. Although some important criteria or objectives have not been considered, the main purpose of this work is to highlight the flexibility of this methodology and the benefits of the proposed prototype which can be further improved by user feedback. For instance, the social media component in the proposed prototype can be used for hosing moderated discussions, to collect user feedback, to educate the community, and to establish collaborative approach for solving such conflicting issues. Individual maps for each of the environmental and economic criteria are shown in Figure 3. Comprehensive descriptions of these factors are given in the next section.

2.3 Environmental Consideration

2.3.1 Distance from Wildlife Habitat

The construction of roads, pipelines, pads, and other infrastructures for drilling operations will disturb vast areas of land and water. Thus, important wildlife habitats represented by diverse species of animals, plants, or other organisms will unavoidably be impacted, fragmented, or even destroyed. Some of the potentially life-threatening impacts to wildlife from hydraulic fracturing are associated with the loss of habitats, contaminated and deteriorated water supplies, air quality, and other living conditions imperative for survival. For the sake of minimizing hazards to wildlife, a minimum separation distance between wildlife habitat and drilling infrastructures must be ascertained. For this study, this distance was calculated using the Euclidean Distance function which measures the straight-line distance from each cell to the source (i.e., distance from wildlife habitat polygons). Table 1 shows the control points and the fuzzy function used for standardizing distances associated with wildlife habitats, rivers, and other criteria. The fuzzy membership functions were used to standardize each criterion to produce continuous possibility values ranging from 0 to 1. Values close to 0 represented full non-membership to the set and values close to 1 represented full membership to the set (Gorsevski et al., 2006; 2012). The control points for distance to wildlife habitats used in this project are 1000 m and 3000 m. Distances below 1000 m were assigned a membership value of 0 (the least suitable) and above 3000 m were given a value of 1 (the most suitable). According to a risk assessment of hydraulic fracturing, the safe distance varies depending on the types of proximal vulnerable environment but should reach a minimum of 1000 m (Ewen *et al.*, 2012). Hence 1000 m is chosen as the least suitable control point and 3000 m is selected as the most suitable control point to account for uncertainties.

2.3.2 Distance from Rivers

Hydraulic fracturing activities could potentially have an adverse impact on water quality due to contamination to surface and ground waters. Some of the threats are associated with surface spills produced in the process of mixing chemicals with water and water injection, flowback fluid from near well pads, and improper disposal of waste water that may leak into adjacent aquifers or be transported through nearby river systems. It's reported that among the 2,500 hydraulic fracturing chemical additives, more than 650 types are carcinogenic (CECUS, 2011). In order to prevent contamination to water resources, isolating the wells from hydraulically vulnerable formations and permanent water bodies is a necessary first step that needs to be considered.

The river data shown in Figure 3 (b) portrays major streams at a scale of 1:1,000, 000 downloaded from the National Atlas of the United States (2012a), converted to raster format, and resampled to 30 x 30 m cell size. The distances between potential well pads and rivers were calculated using a Euclidean Distance function, then two control points (a = 600 m, b = 3000 m) were applied to convert the distance map into a standardized map. It is suggested that the distance between deep hydraulic fracturing wells and water bodies such as rivers and lakes should exceed 600 m (Ewen *et al.*, 2012). Distances less than 600 m will be imposed a membership value of 0 and distances over 3000 m will be given a value of 1 to generate a standardized distance map.

2.3.3 Distance from Lakes

Apart from the contamination produced from hydraulic fracturing activities, the large quantity of water consumption is another great concern. The water is usually obtained from large water bodies, rivers, or ground water. However, abundant extraction from major water bodies, specifically lakes, may highly impact the water supplies for municipal and industrial uses, swimming, fishing, or supporting wildlife. In order to minimize the negative effects on the environment and protect human life, locating the well pads beyond a minimum safe distance from water bodies is of great importance. This study uses two control points (a = 600 m, b = 3000 m) from a risk assessment report of hydraulic fracturing to standardize the distance from potential wells to lakes derived from the Euclidean Distance algorithm. Distances less than 600 m will maintain a membership of 0 indicating the least suitability and over 3000 m will acquire a value of 1 suggesting the best suitability. The lakes data shown in Figure 3 (c) displays the main lakes in the study area at a scale of 1:1000, 000 as of 2012. In this project, the vector data from the National Atlas of the United States was imported in ArcGIS, converted to a raster format, and resampled to 30 x 30 m cell size (2012b).

2.3.4 Distance from Faults

Human-induced earthquakes by hydraulic fracturing have become a focal point of public concern. Withdrawal of gas from the subsurface and injection of hydraulic fluids as well as wastewater into the subsurface might be the cause of these earthquakes. The largest earthquake in central Oklahoma thought to be caused by hydraulic activities and weakening a preexisting fault had a magnitude of 5.6 (Ellsworth, 2013). One prevailing hypothesis for triggering earthquakes from drilling is the tectonic interaction between immense underground wastewater injection and proximal fault slip. As wastewater is injected, the underground pore pressure increases, which can loosen adjacent faults and force the ground to shake, shift, or even tear up in the form of earthquakes. Therefore, maintaining a safe distance from existing faults is a very necessary and vital criterion to avoid potential triggered earthquakes.

It is suggested that a minimum safe distance of 10,000 m between wells and existing fault zones is required to prevent possible earthquakes induced by hydraulic fracturing activities (Nicholson & Wesson, 1992). Figure 3 (d) shows the major faults in the study area shown in. The data were acquired from the Division of Geological Survey (ODNR, 2013). A distance function was applied to determine the distance from faults to possible wells. The distance map was then standardized using a linear increasing function with two control points (a = 10,000 m, b = 30,000 m). Distances less than 10,000 m are assigned a membership value of 0 and more that 30,000 m are given a membership value of 1.

2.3.5 Distance from Urban Areas

Some of the adverse effects generated by hydraulic fracturing that pose a threat to urban areas include heavy truck traffic, noise pollution, air quality, decreased land value, groundwater pollution and methane contamination of drinking water. To avoid any impact on human well-being, quality of human life, and basic human need fulfillment, it is advised to locate hydraulic wells at a minimum safe distance of 1,000 m beyond urban areas (Ewen *et al.*, 2012). The data for urban areas shown in Figure 3 (e) were downloaded from ArcGIS Online in vector format and then was converted into raster format before being employed for deriving the Euclidean Distance map. The distances map was standardized using a linear increasing function with two control points (a=1000 m, b= 10,000 m). Distances less or equal than 1000 m are given a membership of 0 and distances greater than 10,000 m are assigned a membership of 1.

2.4 Economic Consideration

2.4.1 Proximity to Roads

The proximity to major transportation infrastructure is a crucial factor in proper well siting because shale gas development requires drilling rigs and related equipment such as heavy trucks for delivering or removing water, chemicals, wastewater or other site equipment. Thus, access to major transportation is required to lower the cost and facilitate the distribution of gas and oil products efficiently. The road data employed in this study were obtained from the National Atlas of the United States in the format of a shapefile at a scale of 1:1, 000,000 as of 2012; and it consists of interstate and US state roads, as shown in Figure 3 (f) (2012c). The distances between potential wells and roads were calculated using the Euclidean Distance algorithm and then standardized using a linear decreasing function with two control points (a = 1000 m, b = 3000 m). Distances less than 1000 m were assigned a membership of 1 and over 3000 m were assigned a membership values of 0 (Ewen *et al.*, 2012).

2.4.2 Proximity to Pipelines

The proximity to pipelines is a vital consideration for hydraulic fracturing to lower the cost of delivering natural gas to the consumers. The areas with established pipeline networks (i.e., large interstate or intrastate pipelines), for transporting recovered natural gas from the wellhead to market are better candidates for well siting and lower costs. On the contrary, locating hydraulic fracturing wells in areas with inadequate pipelines will require construction of new pipelines, which will likely increase the cost of hydraulic fracturing development and to local communities.

The pipeline data were digitized from an existing map of Oil and Gas Pipelines in Ohio generated by the Ohio Division of Geological Survey (ODGS, 1989). The data were generalized to a single layer and consists of existing interstate and intrastate pipelines associated with gas and oil transmission in the study area. The shapefile data for the main pipelines are shown in Figure 3 (g). The Euclidean Distance function was also applied to derive the distance from pipelines to possible hydraulic fracturing wells. The distance map was standardized using a linear decreasing function with two control points (a = 1000 m, b = 10000 m). Distances below 1000 m were assigned a membership value of 1, distances more than 10000 m were given a membership value of 0, and the membership value decreases from 1 to 0 when distances increase from control point a to control point b.

2.4.3 Proximity to Storage Areas

The proximity to gas storage areas also plays an essential role in establishing hydraulic fracturing wells. The prerequisite of adequate pipeline networks and gas storage areas that are adjacent to wells will facilitate better efficiencies to the consumer network. Because of the confidentiality of the pipelines and the storage area data, perfect precision is not required for this prototype system design in this project. The storage areas data shown in Figure 3 (h) were also digitized from a map of Oil and Gas Pipelines in Ohio generated by the Ohio Division of Geological Survey shown in Figure 3 (h). The distance map calculated using the Euclidean Distance function was standardized and controlled by two points (a= 1000 m, b= 10000 m).

2.4.4 Marcellus Shale Thickness

The organic-thickness of Marcellus Shale indicates the portion of organic-rich rock formations, which is capable of producing gas or other energy sources directly, and it determines the production of the extracted gas as well as the drilling cost. Therefore, the drilling expenses as well the longevity of the gas production vary depending on the Marcellus Shale thickness. The organic-thickness of Marcellus Shale ranges from 0 m at the western limit to 27 m along the southeast border of Ohio. It is economically and practically feasible to locate drilling sites in areas with thicker portions of Marcellus Shale. The data were obtained from U.S. Geological Survey (USGS, 2011) in the format of shapefile shown in Figure 3 (i) and then standardized using a linear decreasing function from a membership value of 0 for the thickness of 0 m and 1 for the thickness of 28 m.

2.4.5 Population Density

Considering market needs for natural gas and delivery efficiency, dense population is a favorable factor for locating hydraulic fracturing. Areas with higher population density possess greater market demands and present better economic prospective. Furthermore, hydraulic fracturing will create a new industry chain that includes geological surveys, drilling operation, water treatment, and gas distribution, which are bound to create jobs and revitalize local economies. The population density map shown in Figure 3 (j) is generated based on the number of residents per square miles using the data obtained from U.S. Census Bureau (2012). It was converted from a shapefile into raster data and afterwards converted into a standardized map using a linear increasing fuzzy membership function with two control points ($a = 20/km^2$, $b = 200/km^2$) employed to produce the standardized population density map. Densities less than $20/km^2$ have a membership value of 0, greater than $200/km^2$ have a value of 1.

3. SYSTEM ARCHITECTURE AND METHODOLOGY

3.1 Weighted Linear Combination (WLC) Approach

The main role of the MCE within SDSS is to enhance and shape public policies and decision making, which is also called Multi-Criteria Decision Analysis (MCDA). MCDA represents a collection of algorithms for aggregating multiple conflicting criteria, evaluating alternatives, and forming a single compromised solution (Gorsevski et al., 2012; Boroushaki and Malczewski, 2010b; Simao et al., 2009; Malczewski, 2006). WLC is one of the most widely used MCDA approaches in GIS-based decision making (Rinner and Malczewski, 2002; Malczewski, 1999).

WLC requires an assignment of weights of relative importance that ranges from 0 to 1 to each criterion map layer. Subsequently, the assigned weights are multiplied by their corresponding cell values in the standardized map layers for obtaining weighted map layers. The weighted map layers are aggregated in order to generate a suitability map where a higher overall score represents a higher suitability. The scores of the environmental and economic considerations are calculated separately using the following equation:

$$A_i = \sum w_j x_{ij} \qquad (i=1, 2, \ldots, n; j=1,2,\ldots,5) \qquad \text{Eq. (1)}$$

where A_i is the suitability score for cell i in each map layer, the weight w_j is a normalized weight for criterion j in environmental or economic consideration with $\sum w_j = 1$, and x_{ij} means the value of cell i from criterion j (Feizizadeh & Blaschke, 2013; Gorsevski et al, 2013). With the weights of all criteria summed to 1, the weight of each criterion is inversely proportional to the sum of other criteria. Any increase in the weight of one criterion will decrease the sum of other criteria. Consequently, the process of determining the relative importance of each criterion is achieved via the trade-offs among weights of congeneric criteria.

3.2 GIS Model

The model shown in Figure 4 demonstrates the core methodologies for the trade-offs between environmental and economic considerations that was designed in ModelBuilder under ArcGIS 10.1 (ESRI, 2011). The model refers to an automated workflow which connects geoprocessing tasks in a logical fashion to accomplish certain GIS functions. This model automatically overlays standardized criterion map layers in weighted order to produce final decision maps for understanding three main components: trade-offs among environmental criteria, trade-offs among economic criteria, and trade-offs between environmental and economic criteria considering exclusion of the pre-determined constraints map.

In the first stage, each criterion from both environmental and economic considerations multiplies its weight and overlays collectively using equation (1) stated above. Each criterion holds a raster layer and the corresponding weight is exhibited as a model parameter which accepts users' input of weight value. In the second phase, the output maps from both environmental and economic considerations repeat the WLC process. The weights which range from 0 to 1 and sum to 1, represent the relative importance of the criteria given by users. Therefore, any increase in the weights of one criterion will lead to the decrease of the weight of the other criterion. Essentially, the process of making decisions is represented by trade-offs between the weights of environmental and economic implications. In the last step, the pre-determined constraints map will be excluded from the criteria map to generate a final map showing the suitability for locations for hydraulic fracturing. The constraint map aggregates three layers, which are national parks, wetlands, and urban areas. Users are also allowed to determine whether those layers will be incorporated as constraints in the analysis. The outputs from the SDSS include three data layers: an environmental layer solution showing the suitability from the environmental factors, an economic layer solution showing the suitability from the economic factors, and a combined suitability layer that aggregates the two objectives.

3.3 System Architecture

The development of the prototype web-based MCE SDSS comprises configuration of the Silverlight-based web application, authorization of geoprocessing services, implementation of the web-based decision making modules, and design of the database. Figure 5 illustrates the system architecture which consists of client, GIS services, and data components. The core component is the ArcGIS Application Programming Interface (API) which integrates ArcGIS Server and map services in a Silverlight application. Once the GIS model is published to ArcGIS Server as a geoprocessing task, it will be run on the server and accessed through web applications supported by Silverlight, which constitutes the connection between the GIS Services side and Client side. On the other hand, ArcGIS API communicates with ArcSDE for Microsoft SQL Server Express with the aid of Windows Communication Foundation (WCF) Services to transmit and store data. A detailed interpretation of the architecture will follow in the subsequent paragraphs.

ArcGIS API for Silverlight supports interactive maps services, geoprocessing tasks from ArcGIS Server, and the utilization of core Silverlight components like data grids, panels, and Silverlight toolkits. Once the GIS model that chains all the geoprocessing tools is published to ArcGIS Server, it's referred to as geoprocessing task. Client requests sent from web browsers, such as Chrome, Mozilla Firefox, or Internet Explorer, will leverage the ArcGIS Web Adaptor to forward requests to the Geoprocessor object, that resides in the ArcGIS API for Silverlight to access the task and obtain information. The ArcGIS Web Adaptor is a setup that connects ArcGIS Server with a web server, Internet Information Service (IIS). The Web Adaptor enables tighter security on ArcGIS Server when exposed to outside users and prevents access to ArcGIS Manager and Administrator Directory. Thereafter, the task will run on the ArcGIS server relying on its enormous computational and GIS analyzing capabilities. After execution, the geoprocessing task will send back the result map service as an image layer through the Geoprocessor object to the web application where the final map will be drawn.

The decision tool aims to assist users with or without GIS knowledge to participate in the decision-making process with an easy-to-use interface. It's designed using Silverlight components for the interface and Visual Basic code support. The frequently employed Silverlight components include data grids, panels, checkboxes, and textboxes. With those interactive controls, users can familiarize themselves with the decision making process and hence improve participating efficiency. The .NET classes facilitate the integration with the .NET Framework class library of controls, components, and value types to access system functionality and perform analytical procedures that comply with the workflow presented in GIS model.

The data side consists of ArcSDE (Spatial Database Engine) for Microsoft SQL Server Express, LINQ To SQL, and WCF Services. ArcSDE is a technology for ArcGIS clients to access geospatial data stored in a relational database management system (RDBMS). RDBMS offers a forthright structure for storing, querying, retrieving, and managing data, together with ArcSDE and ArcGIS Objects making a Geodatabase model. This project relies on Microsoft SQL Server Express as its RDBMS, which creates three tables for storing non-spatial data from users' input. Registered service data folders are verified locations that can be accessed by ArcGIS Server, they contains the geoprocessing models, inputs, and outputs GIS data. Even though geoprocessing models and inputs maps will be published to ArcGIS Server, geoprocessing and map services will continue to reference the models and maps without copying the data onto ArcGIS Server. This prevents redundant data storage and allows flexible data management. LINQ to SQL is a .NET framework that provides direct management of relational data and direct mapping of a Microsoft SQL Server database to .NET classes. When the application runs, LINQ to SQL translates requests sent from the GIS Service side to SQL and sends them through WCF Services to the database for execution. When the database returns the results, LINQ to SQL translates the command sent from WCF Services back to instructions that can be understood by the GIS Service. WCF is a .NET framework for building service-oriented applications. In this project, WCF Service uses LINQ to SQL to retrieve the data from the database, and return it to the Silverlight client application.

4. USER INTERFACE AND SYSTEM DESCRIPTION

The SDSS prototype takes advantage of ArcGIS Server, ArcGIS API for Silverlight, and the Visual Studio environment to provide an interactive interface as well as synchronous geographic data processing and display. The prototype aims to facilitate distributed environment that can be used as an educational tool and for consensus decision making with an easy-to-use interface and straightforward procedures. The navigation bar consists of menu icons for different components of the SDSS organized by hierarchy levels following the logic of the decision-making process. A comprehensive description of the system is discussed below.

The GUI of the hydraulic fracturing SDSS prototype is shown in Figure 6. The GUI consists of general map functions like legend, zoom in, zoom out, and scale bar which enable users to check the geographic information and basic operations available in the SDSS tool. Furthermore, the study area map located in the interface center is used to familiarize the users with the basic location settings and the extent of the case study area. The legend panel shows what is being viewed and users can choose to display layers of interest grouped by categories by checking and unchecking the layers. The flexibility of displaying or hiding particular layers enables a better visualization of the spatial criteria which provides the users with a better understanding of the criteria for the spatial decision-making process. The navigation bar contains logical modules that guide the decision process and includes the following buttons: Welcome, Background, Spatial Decision Support Tool, Group Decisions, Help, and social media sharing function displayed from left to right.

The "Welcome" module shown in Figure 7 familiarizes the users with an introduction to the project with the study area map, brief guidance on utilizing the tool, and links to various system components. In addition, the "Background" module provides information about geological background, benefits, and risks of hydraulic fracturing, current exploitation in Ohio, data acquisition, methodologies involved in this project, and description of the criteria as well as their relationship with hydraulic fracturing. This module aims to assist users in establishing in-depth understanding of hydraulic fracturing and the decision making approaches associated with the SDSS tool so as to well take advantage of it.

The core component of the system is the "Spatial Decision Support Tool", which is invoked by clicking the button, which causes a popup dialog to appear. As shown in Figure 8, the tool consists of four successional steps for implementing constraints, environmental criteria, economic criteria, and aggregation of environmental and economic objectives. Each dialog contains navigation buttons such as "Next", "Previous", or both to allow users to proceed or return easily whenever they want to modify choices or values. In the first step, users make a choice about which layers should be included as priori constraints, that is, the selected layer will exclude geographic areas for possible hydraulic fracturing sites. In the following step for environmental consideration, there are a total of five criteria available for selection and inclusion in the analysis. For all criteria included in the analysis, a weight value is required based on users' personal understanding of the decision problem. The sum of all the weights should equal 1, otherwise an error message will appear to prevent the user from entering into the next module. A low weight value represents a low criterion importance, but high criterion scores can compensate for low weights. The next module, on economic criteria, also deals with five criteria following the same procedure as in the previous step. Finally, setting a value for the trade-off between environmental and economic consideration is the last step of the process. The module uses a scroll bar with an initial value set at the center that imposes equal criteria importance (50%) for both objectives. Users can adjust the importance values for both objectives by moving the slider to either left or right. Increase in one side will cause decrease in the other side synchronously. By clicking “Next” in this stage, the dialog will be dismissed and a decision map will be displayed.

Figure 9 exhibits an example of a final decision map for the suitability analysis of hydraulic fracturing. The legend in the upper left corner shows the suitability scores associated with the map. Higher values represent better suitability, namely, the areas with dark blue color are preferable locations in this example. As the highest score in this example, 0.54 represents the uncertainty of the decision making process. The hollow areas are excluded from the analysis because constraints such as national parks, wetlands, urban areas, or any combination of the three were used in the decision process.

The “Help” module allows participants to obtain a comprehensive understanding of how to use the SDSS tool, how to better understand the implications from drilling activities, and how to broaden awareness of the importance of this issue to a wider audience. For example, the four social media sharing modules at the right end of the menu bar are intended to facilitate discussions, debates and to educate public users about possible implications of hydraulic fracturing.

Finally the “Group Decision” module shows the results from all users who participated in the SDSS process. Figure 10 shows a hypothetical example for visualization of the results generated by a total of 20 users. For example, the boxplots show the quantitative data for examining key statistical properties for the weights associated with each criterion. The boxplots use the same hierarchical structure of the decision process for visualization of individual criteria and spatial trade-offs between environmental and economic implications.

5. DISCUSSION AND CONCLUSIONS

The goal of this research was to demonstrate a SDSS prototype that can be used for site-selection analysis for hydraulic fracturing. The prototype considers a set of different influencing criteria that can be used for trade-off analysis to better understand implications of environmental and economic consequences. Although the selection of criteria in this study was limited to available public data sets and recommendations based on previous research, the approach offers flexibility for inclusion of different evaluation criteria, objectives or parameters based on site specific problems and requirements (Davis and Robinson, 2012; EPA, 2012; Engelder and Lash, 2008;). According to Malczewski (1999), the determination of evaluation criteria for solving any complex problems is a multistage, iterative, and ever-improving process. Thus, acquiring comprehensive and persuasive criteria during the planning process requires an involvement of representatives with different backgrounds and increased understanding for consensus building (Tang, 2005).

The strength of this methodology is the flexibility for an asynchronous deployment, modification and customization to address different research issues, alteration of criteria or applications, and usage for different purposes such as group decision making, participatory GIS, consensus building, and for outreach or education on controversial issues such as hydraulic fracturing. For instance, involvement of public input in the planning process is essential but it should be clear that wide public involvement does not necessarily lead to better decision-making. Thus, implementation of this prototype in terms of public policy education may allow better reflective judgments and efficient public involvements for conceptualized and informed decision choices. In addition, the deployment of this prototype can empower marginalized key players who are directly affected by a decision and its planning consequences.

The WLC approach implemented in this study is one of the popular methods being employed in various decision-making problems. The choice of method usually depends on the complexity of the problem, the accuracy requirement, the operability of evaluating the criteria, and the ease of quantifying the measurements of criteria. For instance, pairwise comparison or trade-off analysis could be considered if specific numerical or accurate rank ordering is required; on the other hand, a ranking or rating method could be applied on the assumption that numerical weights are difficult to be assigned (Malczewski, 1999). This study aims to generate a suitability decision map indicating the suitability value across the space. The trade-offs occur in the process of imposing weights and the final suitability score is developed through mathematical computation guided by WLC. Further research could explore other methods to achieve a more comprehensive and multi-perspective evaluation using adequate selection of representative participants.

With the web-based SDSS for hydraulic fracturing site-selection, both critical environmental and economic factors are incorporated in the spatial trade-offs to generate a suitability map for planning purposes. As a complex and controversial problem, the utilization of MCE methods and techniques greatly increase the flexibility of the site-selection process. GIS-based MCE consists of consecutive data transformations: standardization of spatial data layers into a common scale, assignment of importance preference as numerical weights, and integration of standardized data with corresponding weights to generate a final appraisal score (Nyerges and Jankowski, 2012). This research utilizes two control points and linear increasing or decreasing functions to standardize the data layers; the weight values should range from 0 to 1 and all weights of criteria for either environmental or economic factors should sum up to 1; WLC uses criterion importance score to multiply each cell value in the corresponding standardized map to produce appraisal scores.

The computed suitability score in the final decision map represents a measurement for sorting potential alternatives quantitatively from most to least desirable. In addition, the standardization of the data, the usage of the control points, and the final suitability score are all utilized to account for potential uncertainty that occurs during decision-making procedures. However, the main emphasis of this research is on the implementation of this innovative approach in hydraulic fracturing site selection instead of creating an infallible SDSS to make perfect decisions. The development of this tool is inspired by existing SDSS attempts and will provide successors with new perspectives.

The SDSS prototype combines client, GIS services, and data side as a whole, which respectively employs Silverlight, ArcGIS API for Silverlight together with ArcGIS

Server, and ArcSDE for SQL Server as its execution tools. This architecture is backed up with enterprise GIS and database software, hence inheriting rich mapping and database operational capabilities. However, the limitation in the compatibility of Silverlight with other database server such as PostgreSQL and the requirement for installation of the Silverlight plug-in might impact the penetration and popularity of the prototype system.

REFERENCES

Alcorn R., Panter K.S., Gorsevski P.V., 2013. A GIS-based volcanic hazard and risk assessment of eruptions sourced within Valles Caldera, New Mexico. Journal of Volcanology and Geothermal Research, 267:1-14.

Alonso S., Herrera-Viedma E., Chiclana F., 2010. A web based consensus support system for group decision making problems and incomplete preferences[J]. Information Sciences, 2010, 180(23): 4477-4495.

Arthur, J. D., Bohm, B., & Layne, M., 2008. Hydraulic fracturing considerations for natural gas wells of the Marcellus shale. The Ground Water Protection Council 2008 Annual Forum. Accessed March 4, 2013, http://www.dec.ny.gov/docs/materials_minerals_pdf/GWPCMarcellus.pdf.

Ayalew, L., Yamagishi, H., & Ugawa, N., 2004. Landslide susceptibility mapping using GIS-based weighted linear combination, the case in Tsugawa area of Agano River, Niigata Prefecture, Japan. Landslides, 1(1), 73-81.

Aydin N.Y, Kentel E, Duzgun S., 2010. GIS-based environmental assessment of wind energy systems for spatial planning: A case study from Western Turkey. Renew Sustain Energy Rev 2010; 14:364–73.

Berry, R., Higgs, G., Fry, R., Langford, M. 2011. Web-based GIS approaches to enhance public participation in wind farm planning. Transactions in GIS, 15, 147-172.

Boroushaki, S., & Malczewski, J., 2010a. ParticipatoryGlS: A Web-based Collaborative GIS and Multi-criteria Decision Analysis. Urisa Journal, 22(1), 23.

Boroushaki, S., & Malczewski, J., 2010b. Using the fuzzy majority approach for GIS-based multicriteria group decision-making. Computers & Geosciences, 36(3), 302-312.

Buckingham, L., 2011. Pennsylvania Marcellus shale development & water. ENVR-102. Accessed Feb. 18, 2013, http://oneplanetassociates.com/wp-content/uploads/2011/08/Marcellus-Paper-Final-PDF.pdf.

Chakroun, H., & Benie, G., 2005. Improving Spatial Decision Support Systems. Applied GIS, 1(1).

Chen, C., Lee, C., Tseng, C., & Chen, C., 2013. Application of GIS for the determination of hazard hotspots after direct transportation linkages between Taiwan and China. Natural Hazards, 66(2), 191-228.

Choi, J., Engel B. and Farnsworth R., 2005. Web-Based GIS and Spatial Decision Support System for Watershed Management. Journal of Hydro-informatics, 7(3), 165-174.

Committee on Energy and Commerce U.S. (CECUS), 2011. Chemicals Used in Hydraulic Fracturing. Accessed Apr. 4, 2014, http://democrats.energycommerce.house.gov/sites/default/files/documents/Hydraulic-Fracturing-Chemicals-2011-4-18.pdf.

Damos P, & Karabatakis S., 2013. Real time pest modeling through the World Wide Web: decision making from theory to praxis[J]. IOBC-WPRS Bulletin, 91: 253-258.

Davis J. B. & Robinson, G.R., 2012. A Geographic Model to Assess and Limit Cumulative Ecological Degradation from Marcellus Shale Exploitation in New York, USA. Ecology and Society, 17(2):25.

Donevska K.R., Gorsevski P.V., Jovanovski M, Peshevski I. 2012. Regional non-hazardous landfill site selection by integrating fuzzy logic, AHP and Geographic Information Systems. Environmental Earth Sciences, 67:121-131.

Drobne, S., and Lisec A., 2009. Multi-attribute Decision Analysis in GIS: Weighted Linear Combination and Ordered Weighted Averaging. Informatica (03505596), 33.4.

Ellsworth, W., 2013. Injection-Induced Earthquakes. Science, 341(6142).

Energy Information Administration (EIA), 2011. Review of Emerging Resources：U.S. Shale Gas and Shale Oil Plays. Accessed April, 2013, http://www.eia.gov/analysis/studies/usshalegas/pdf/usshaleplays.pdf.

Energy Information Administration (EIA), 2012. U.S. Energy Information Administration. Accessed April, 2013, www.eia.gov.

Engelder, T., & Lash, G.G, 2008. Marcellus shale play's vast resource potential creating stir in Appalachia. The American Oil & Gas Reporter. Accessed Feb. 25, 2013, http://www.aogr.com/index.php/magazine/cover-story/marcellus-shale-plays-vast-resource-potential-creating-stir-in-appalachia.

ESRI 2011. ArcGIS Desktop: Release 10.1. Redlands, CA: Environmental Systems Research Institute.

Ewen, C., Borchardt, D., Richter, S., Hammerbacher, R., 2012. Hydrofracking Risk Assessment, Executive Summary, Study concerning the safety and environmental compatibility of hydrofracking for natural gas production from unconventional reservoirs. ISBN 978-3-00-038263-5.

Feizizadeh, B., & Blaschke, T., 2013. GIS-multicriteria decision analysis for landslide susceptibility mapping: comparing three methods for the Urmia lake basin, Iran[J]. Natural hazards, 65(3): 2105-2128.

Gorsevski, P.V., Jankowski, P., Gessler, P.E., 2006. An heuristic approach for mapping landslide hazard by integrating fuzzy logic with analytic hierarchy process. Control and Cybernetics, 35(1): 121-146.

Gorsevski, P. V., Donevska, K. R., Mitrovski, C. D., & Frizado, J. P., 2012. Integrating multi-criteria evaluation techniques with geographic information systems for landfill site selection: A case study using ordered weighted average. Waste Management, 32, 287-296.

Gorsevski, P. V., Cathcart, S. C., Mirzaei, G., Jamali, M. M., Ye, X., & Gomezdelcampo, E., 2013. A group-based spatial decision support system for wind farm site selection in northwest Ohio. Energy Policy, 55(C), 374-385.

Grassi, S., Chokani, N., Abhari, R., 2012. Large scale technical and economical assessment of wind energy potential with a GIS tool: Case study Iowa. Energy Policy 45, 73-85.

Hall, K. B., 2011. Regulation of Hydraulic Fracturing Under the Safe Drinking Water Act. Buffalo Environmental Law Journal, 2011, 19, 1-219.

Hayes, T., 2009. Sampling and analysis of water streams associated with the development of Marcellus shale gas. Marcellus Shale Coalition. Accessed March 2, 2013, http://www.bucknell.edu/script/environmentalcenter/marcellus/default.aspx?articleid=14.

Hefley, W. E., Seydor, S. M., Bencho, M. K., Chappel, I., Dizard, M., Hallman, J., & Lampe, F., 2011. The economic impact of the value chain of a Marcellus shale well. Working Paper. University of Pittsburgh. Accessed Mar 14, 2014, http://ssrn.com/abstract=2181675.

Jankowski, P., & Nyerges, T., 2003. Toward a framework for research on geographic information-supported participatory decision-making. URISA Journal, 15(1), 9-17.

Jankowski, P., & Stasik, M.,1997. Design considerations for space and time distributed collaborative spatial decision making. Journal of Geographic Information and Decision Analysis, 1(1), 1-8.

Jenner, S, & Lamadrid, A.J., 2012. Shale gas vs. coal. Coal (March 18, 2012),

Joseph-Williams N., Jones M., Griffiths J., et al., 2013. The cost implications of informed decision-making: a mathematical simulation model of the potential financial effects of a web-based prostate specific antigen decision aid[J]. European Journal for Person Centered Healthcare, 1(1): 193-201.

Kargbo, D. M., Wilhelm, R. G., & Campbell, D. J., 2010. Natural gas plays in the Marcellus shale: Challenges and potential opportunities. Environmental Science & Technology, 44(15), 5679-5684.

Malczewski, J., 2006. GIS-based multi-criteria decision analysis: A survey of the literature. International Journal of Geographical Information Science, 20(7), 703-726.

Malczewski J, 1999. GIS and multicriteria decision analysis[M]. John Wiley & Sons.

Michanowicz, D., Malone, S., Kelso, M., Christen, C., & Volz, C.D., 2010. Utilizing Web-based public participation geographical information systems: Filling gaps of the Marcellus shale natural gas industry. Accessed Mar 14, 2013, http://www.chec.pitt.edu/documents/Marcellus%20Shale/MichanowiczNMaloneICSIT2011.pdf.

Nicholson, C., Wesson, R. L., 1992. Triggered earthquakes and deep well activities. Pure and Applied Geophysics, 139(3-4), 561-578.

Nyerges, T. L. & Jankowski, P. 2012. Regional and urban GIS: a decision support approach. Guilford Press.

Ohio Department of Natural Resources (ODNR), 2013. Accessed July, 2013, http://ohiodnr.gov/.

Ohio Environmental Protection Agency (Ohio EPA), 2013. Managing Water Use for Shale Drilling. Retrieved Mar 4th, 2013, Accessed April, 2013, http://www.epa.ohio.gov/Portals/0/general%20pdfs/Considerations%20for%20Public%20Water%20Systems%20Prior%20to%20Providing%20Raw%20or%20Treated%20Water%20to%20Oil%20and%20Natural%20Gas%20Companies.pdf.

Ohio Division of Geological Survey(ODGS), 1989. Oil and Gas Pipelines in Ohio. Ohio Department of Natural Resources, Division of Geological Survey, page-size map, scale: 1:1,900,000.

Penn State Public Broadcasting (PSPB), 2013. Explore Shale-- An exploration of natural gas drilling and development in the Marcellus Shale. Accessed April, 2013, http://exploreshale.org.

Pool, R., 2011. Energy crisis postponed? Power Shale Gas. Engineering & Technology, 2011, 6, 5, 88-90, IET.

Power, J. D., 2002. Building Web-Based Decision Support Systems. Studies in Informatics and Control, Vol. 11, No. 4, 2002, 291-302.

Purucker, S. T., Stewart, R. N., & Welsh, C. J. E., 2009. SADA: Ecological risk based decision support system for selective remediation. Decision Support Systems for Risk-Based Management of Contaminated Sites, 1-18.

Rahm, D., 2011. Regulating hydraulic fracturing in shale gas plays: The case of Texas. 2011, 39, 5, 2974-2981.

Rahm, B. G., Bates, J. T., Bertoia, L. R., Galford, A. E., Yoxtheimer, D. A., & Riha, S. J., 2013. Wastewater management and Marcellus shale gas development: Trends, drivers, and planning implications. Journal of Environmental Management, 120, 105-113.

Rinner, C., & Malczewski, J., 2002. Web-enabled spatial decision analysis using ordered weighted averaging (OWA). Journal of Geographical Systems, 4(4), 385-403.

Roger, K. and Cottrell, J.R., 2012.The Nearly Indefinite and Important Role of GIS in the Marcellus Play. Available online from: http://www.shaleplayohiovalley.com/page/content.detail/id/500289.html.

Romich, E., & Schumacher, S., 2012. Summary of Hydraulic Fracturing in Ohio. Monroe County Community Development Newsletter. Accessed May 5, 2014, http://ohioline.osu.edu/sh-fact/pdf/Summary_of_Hydraulic_Fracturing_in_Ohio_SOGD-DEV1-12.pdf.

Simao, A., Densham, P. J., & Haklay, M., 2009. Web-based GIS for collaborative planning and public participation: An application to the strategic planning of wind farm sites. Journal of Environmental Management, 90(6), 2027-2040.

Soeder, D. J., & Kappel, W. M., 2009. Water Resources and Natural Gas Production from the Marcellus shale US Department of the Interior, U.S. Geological Survey Fact Sheet 2009–3032, 6 p.

Steiner, J. E., 2012. Marcellus Shale Exploration in Greene County, Pennsylvania: A Land Cover Study of the Cumulative Effects of Forest Fragmentation in Well Pad Site Selection and Construction. Dissertation Abstracts. Indiana University of Pennsylvania, Accessed Mar 18, 2014, http://dspace.iup.edu/handle/2069/766.

Stewart L.R., Farver J.R., Gorsevski P.V., and Miner J.G., 2014. Spatial prediction of blood lead levels in children in Toledo, OH using fuzzy sets and the site-specific IEUBK model. Applied Geochemistry, 45:120-129

Tang, T., Zhao, J., & Coleman, D. J., 2005. Design of a GIS-enabled Online Discussion Forum for Participatory Planning. Paper presented at the Proceedings of the 4th Annual Public Participation GIS Conference.

Taranu, J. P., 2009. Building Consensus Using a Collaborative Spatial Multi-criteria Analysis System. University of Waterloo, retrieved from http://uwspace.uwaterloo.ca/bitstream/10012/4246/1/John%20Taranu%20-%20MES%20Thesis.pdf.

The National Atlas of the United States, 2012a. One Million-Scale Streams. Accessed April 1, 2013, http://nationalatlas.gov/mld/1strmsl.html.

The National Atlas of the United States, 2012b. One Million-Scale Waterbodies and Wetlands. Accessed April1, 2013, http://nationalatlas.gov/mld/1lakesp.html.

The National Atlas of the United States, 2012c. One Million-Scale Major Roads.

Accessed April1, 2013, http://nationalatlas.gov/mld/1roadsl.html.

GWPC, 2009; U.S. EPA, 2004; IOGCC, 2002. The Facts about Hydraulic Fracturing.

Ohio Department of Natural Resources. Accessed April, 2013, http://oilandgas.ohiodnr.gov/portals/oilgas/pdf/Facts-about-HFracturing.pdf.

U.S. Census Bureau, 2012. Accessed October 20, 2013, http://quickfacts.census.gov/qfd/states/39000.html.

U.S. Geological Survey (USGS), 2012. Accessed April, 2013, http://www.usgs.gov/newsroom/article.asp?ID=3419#.U9RWRLJfEdB.

U.S. Geological Survey (USGS), 2010. Accessed April, 2013, http://pubs.usgs.gov/fs/2010/3100/pdf/fs2010-3100.pdf.

U.S. Geological Survey (USGS), 2011. Accessed April, 2013, http://www.usgs.gov/.

United States Environmental Protection Agency (EPA), 2012. Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources. Accessed December, 2012, http://www.epa.gov/hfstudy/pdfs/hf-report20121214.pdf.

Zhang, Y.L., Sugumaran, R., McBroom, M., DeGroote, J., & Barten, R. L. K. P. K., 2011. Web-based spatial decision support system and watershed management with a case study. International Journal of Geosciences, 2, 195-203.

APPENDIX A: FIGURES

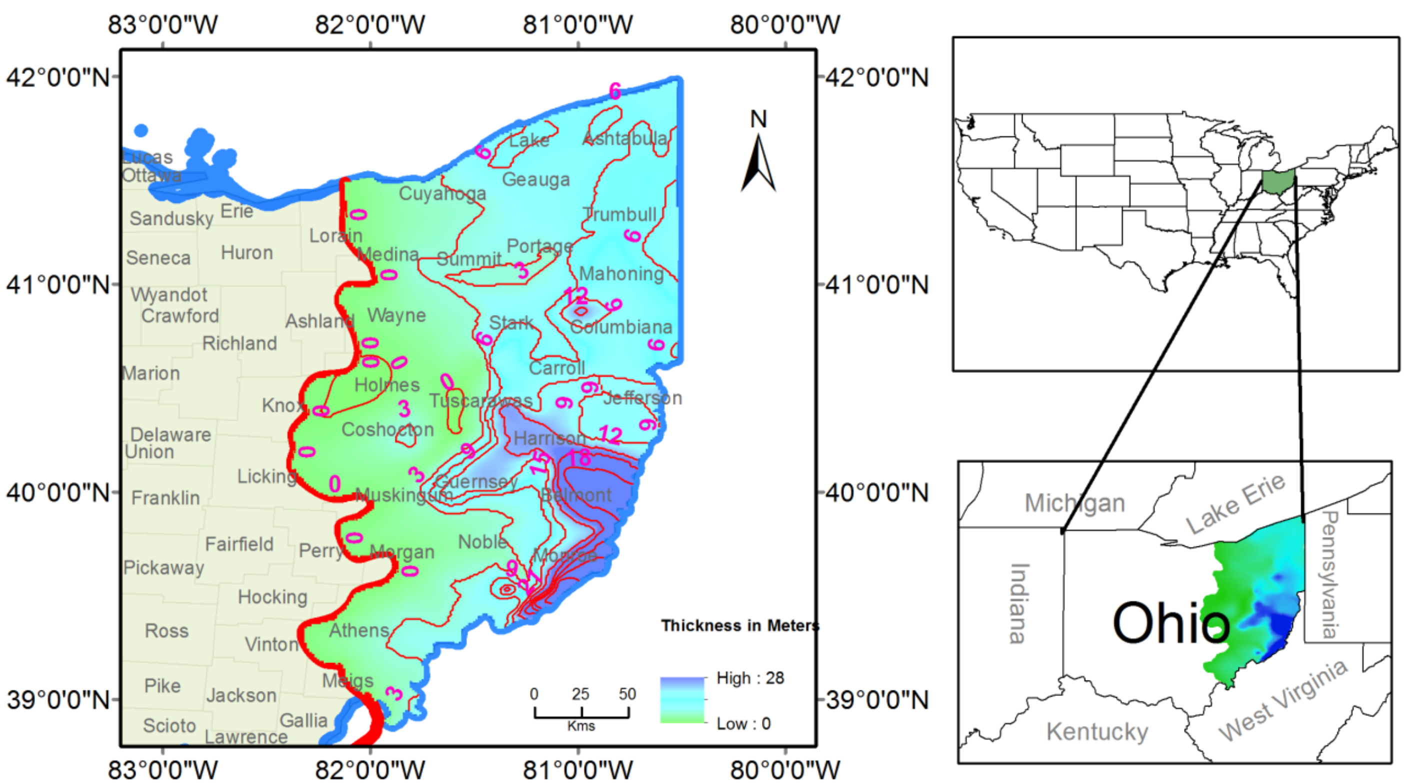

Figure1. Location of the study area in eastern Ohio.

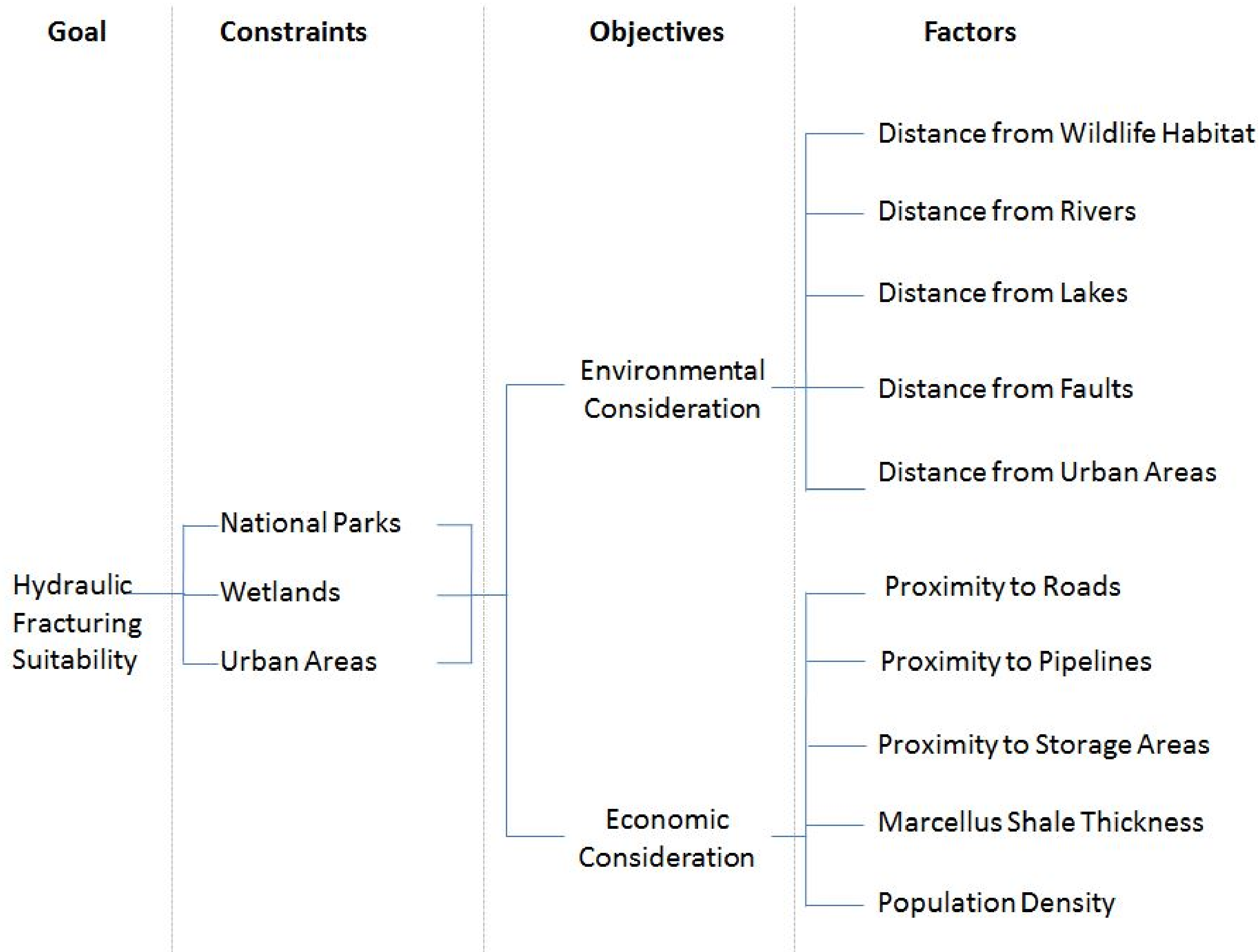

Figure 2. Hierarchical structure of the evaluation criteria.

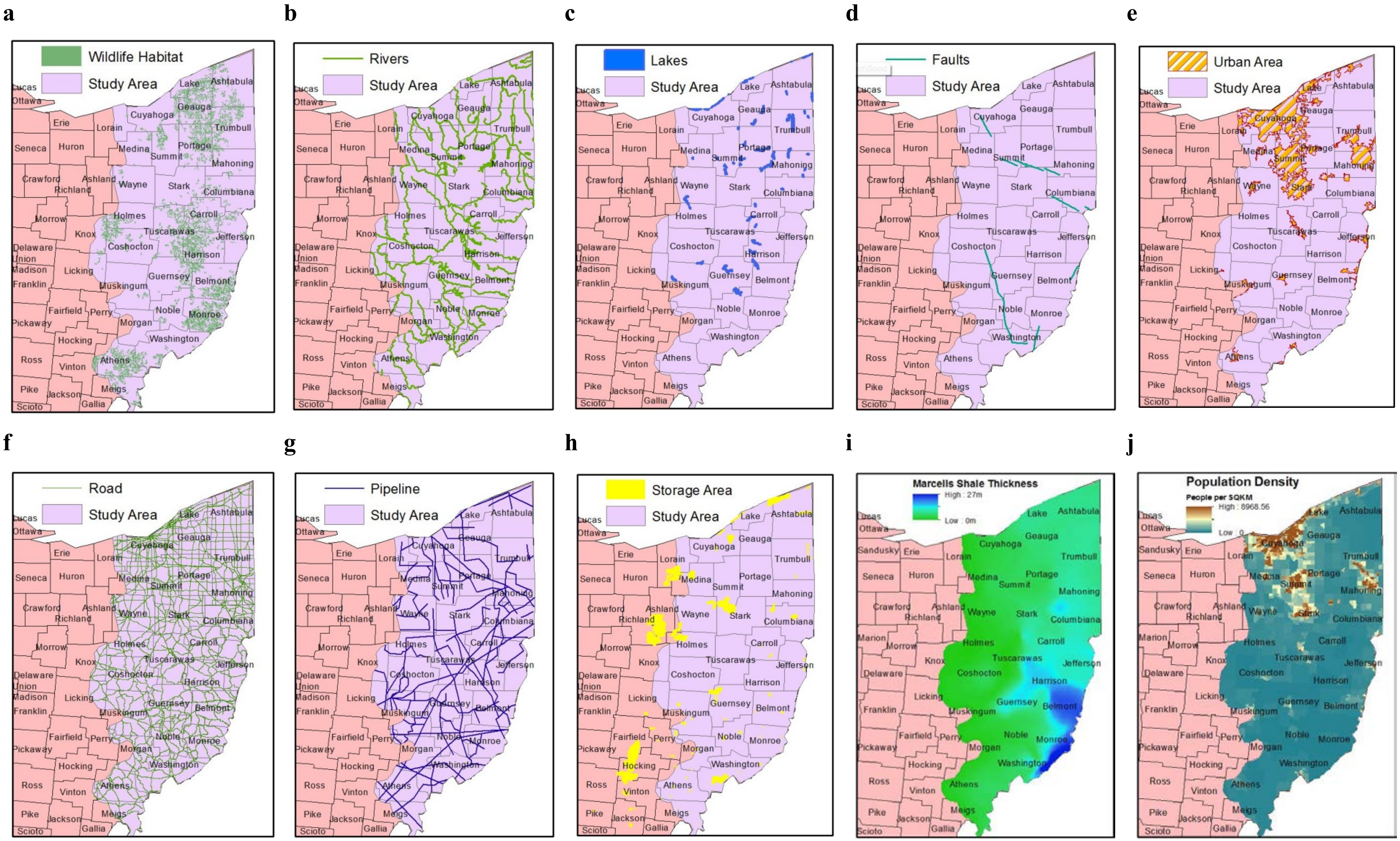

Figure 3. Environmental factors for: (a) Wildlife Habitat, (b) Rivers, (c) Lakes, (d) Faults, (e) Urban Areas; and Economic Factors: (f) Roads, (g) Pipelines, (h) Storage Areas, (i) Marcellus Shale Thickness, and (j) Population Density.

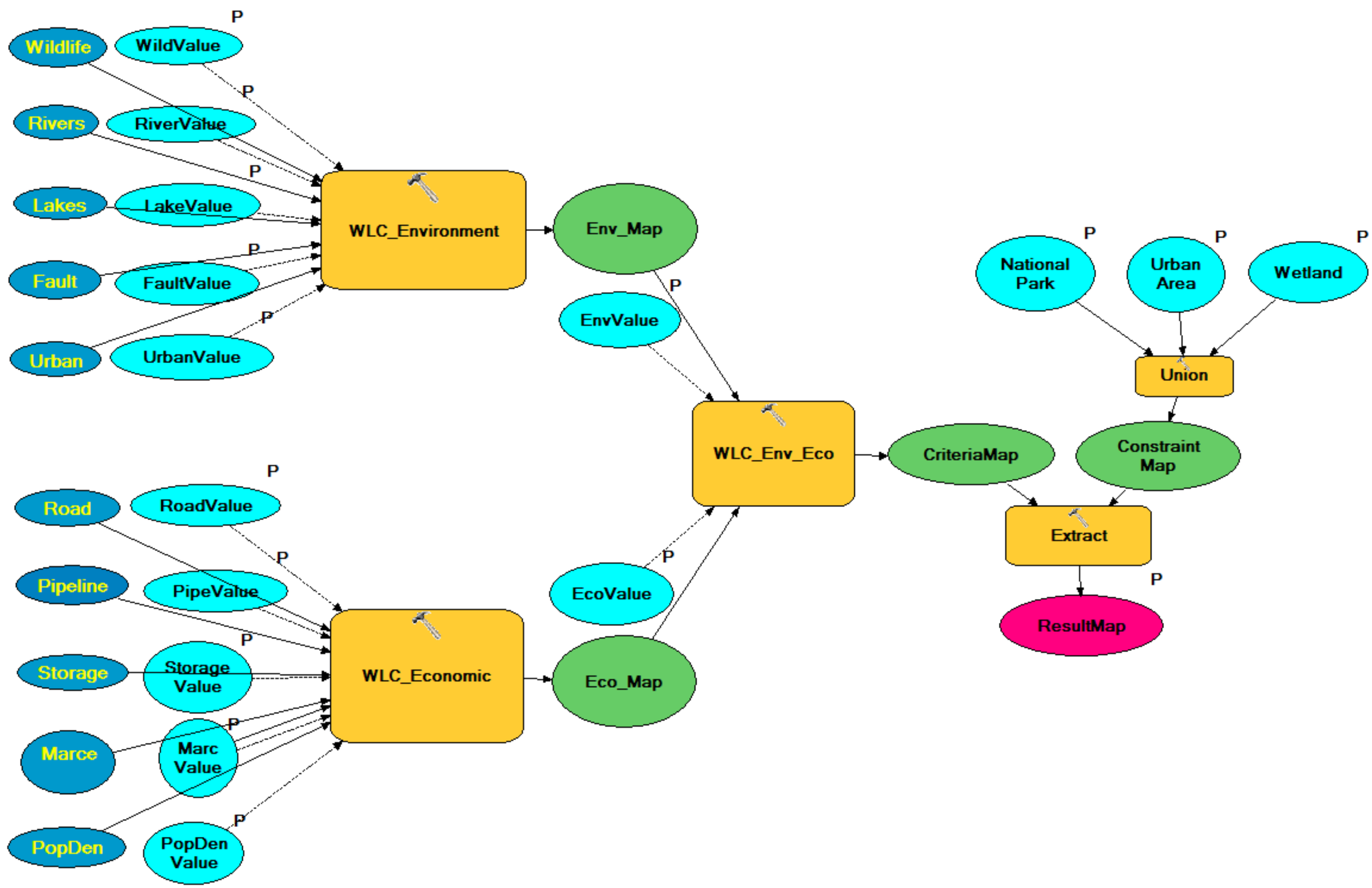

Figure 4. Model for trade-offs between environmental and economic criteria.

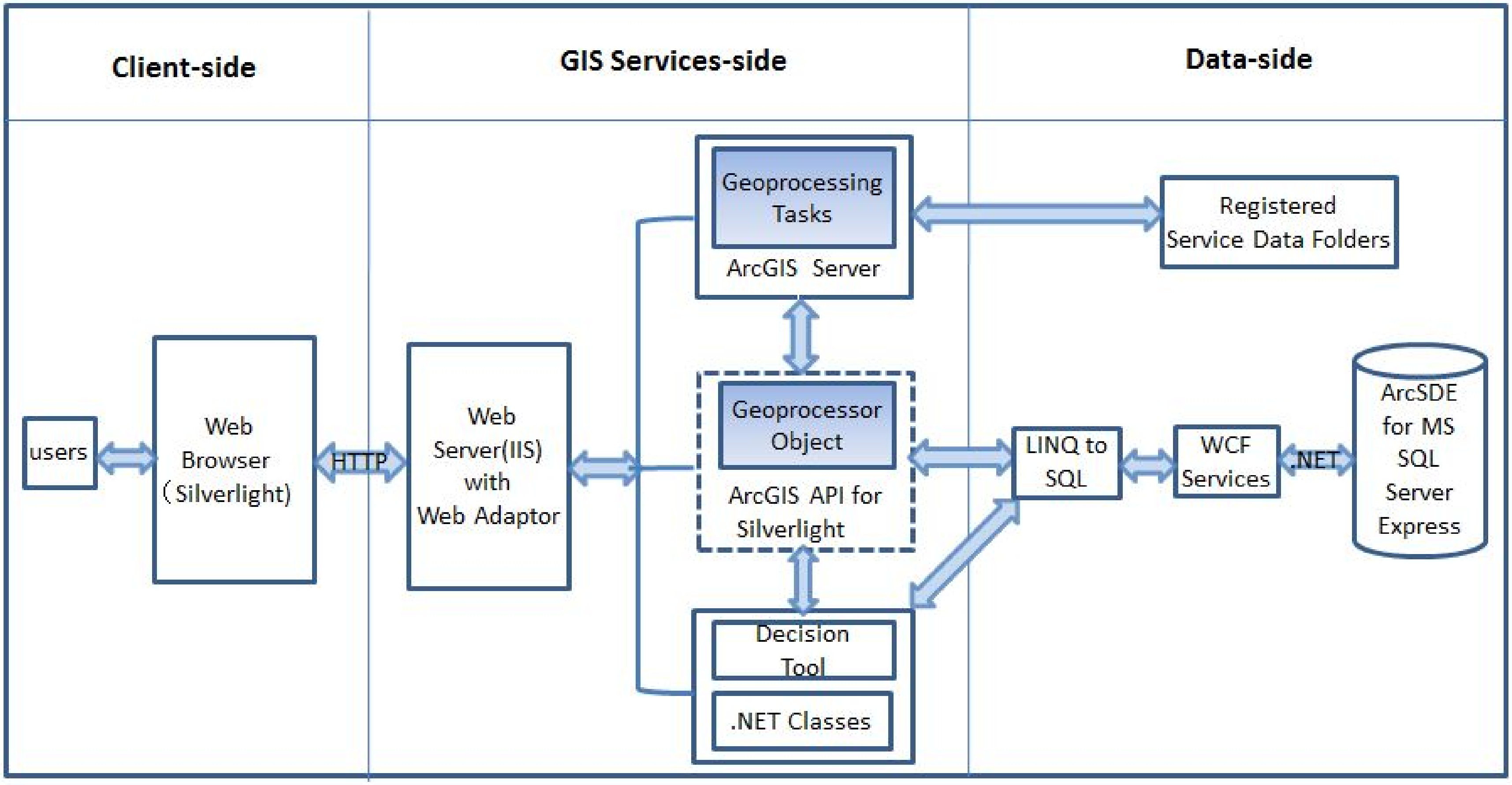

Figure 5. System architecture.

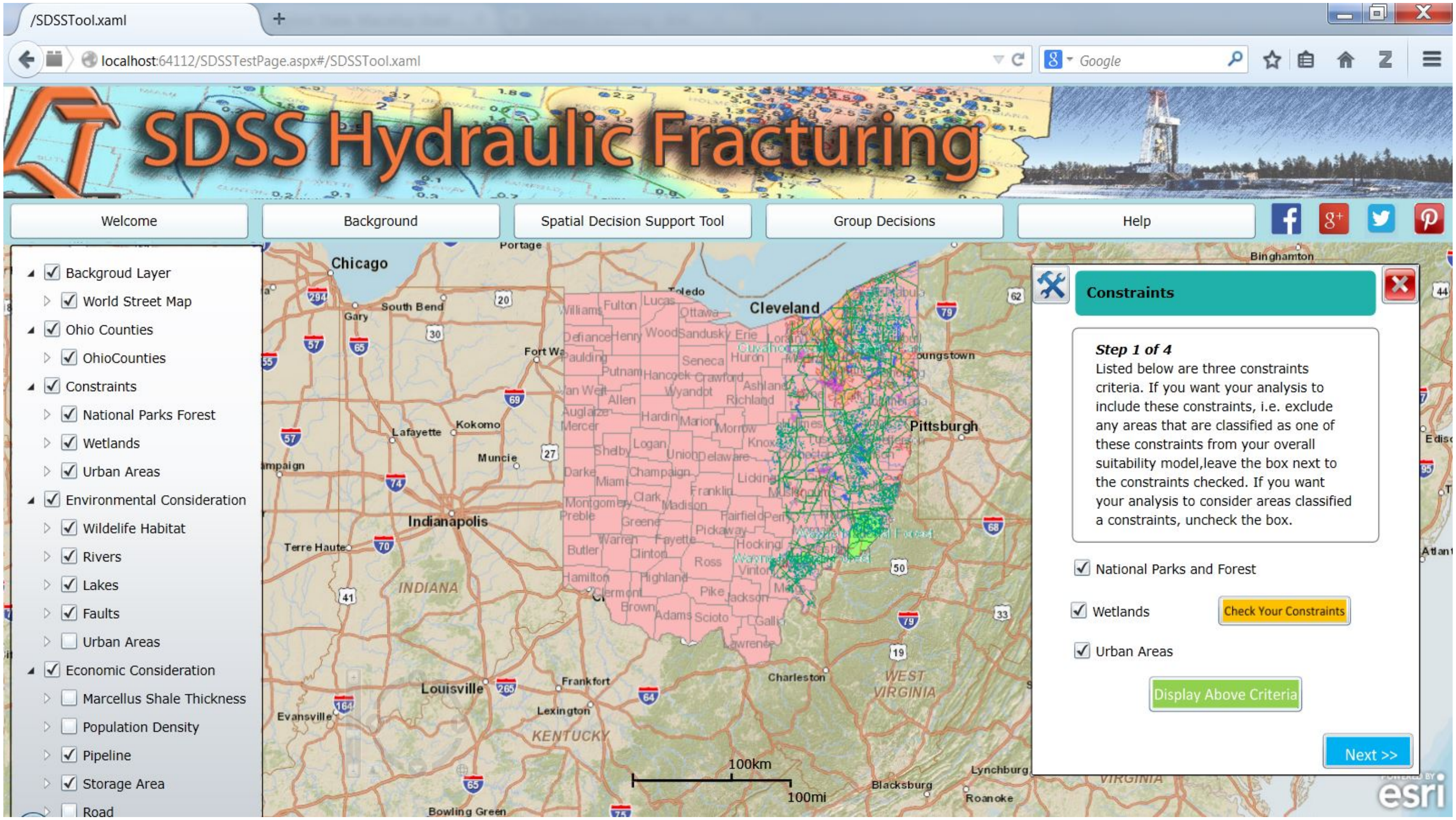

Figure 6. SDSS interface.

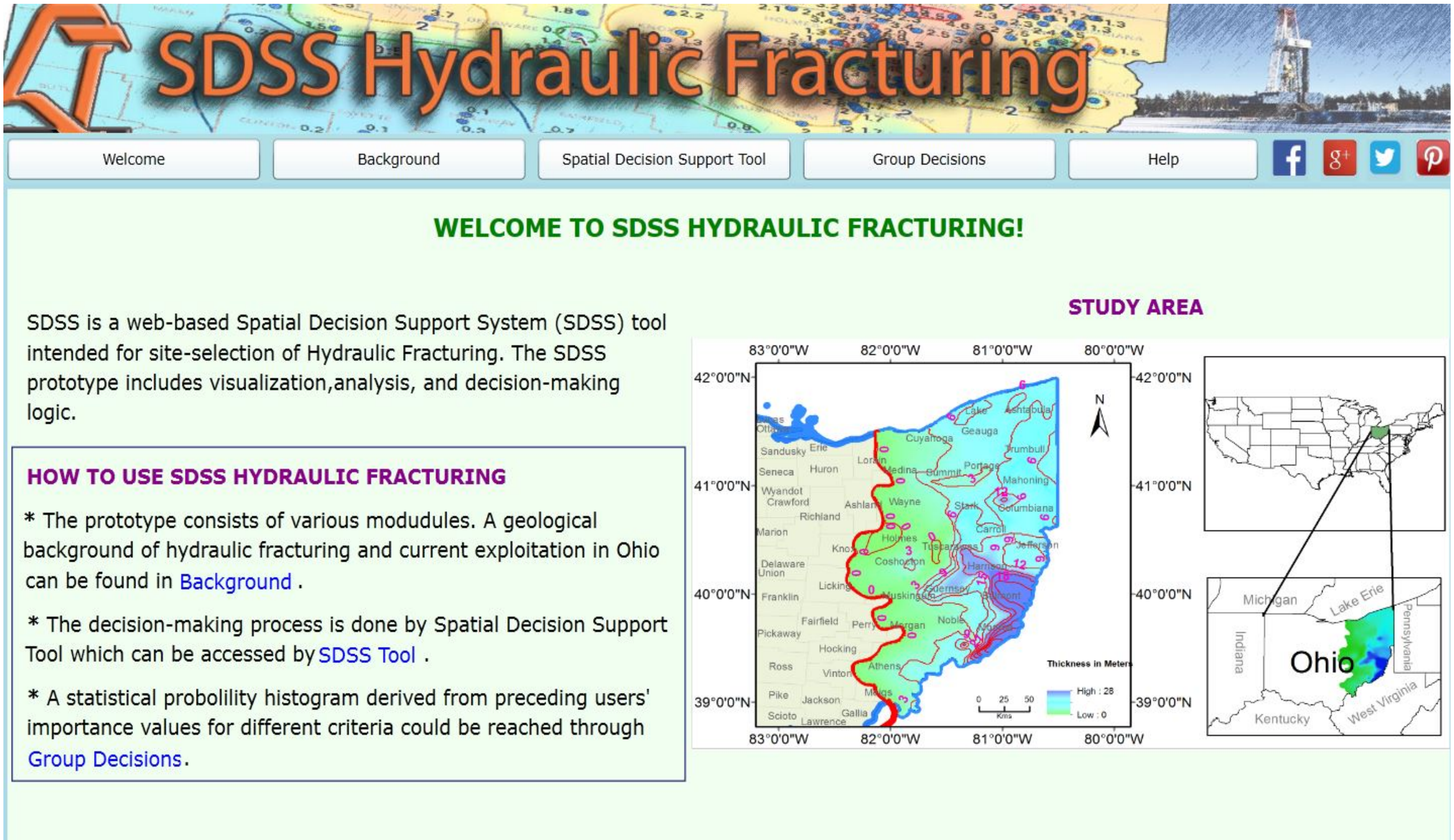

Figure 7 Welcome page of the SDSS.

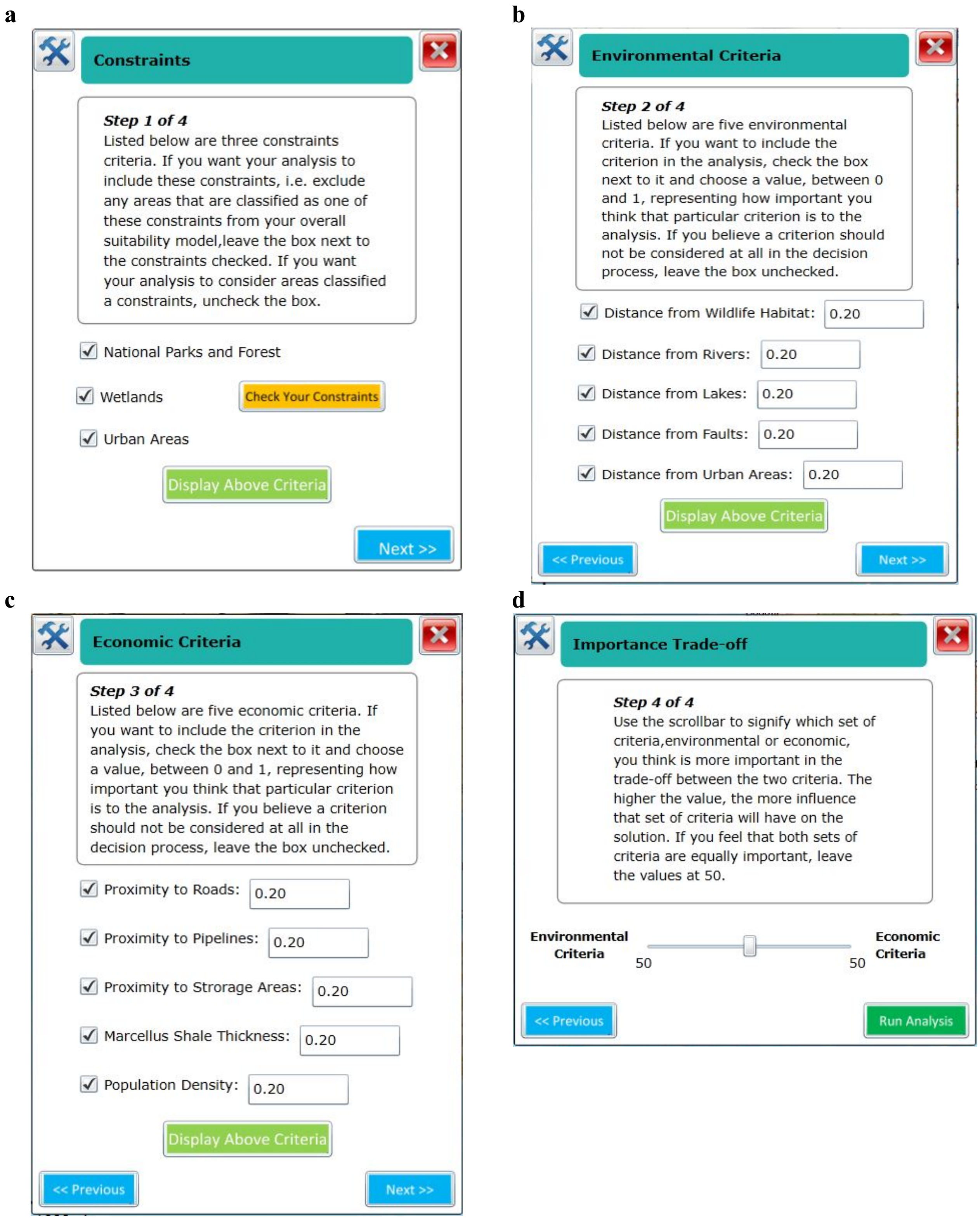

Figure 8. Interface of spatial decision support tool

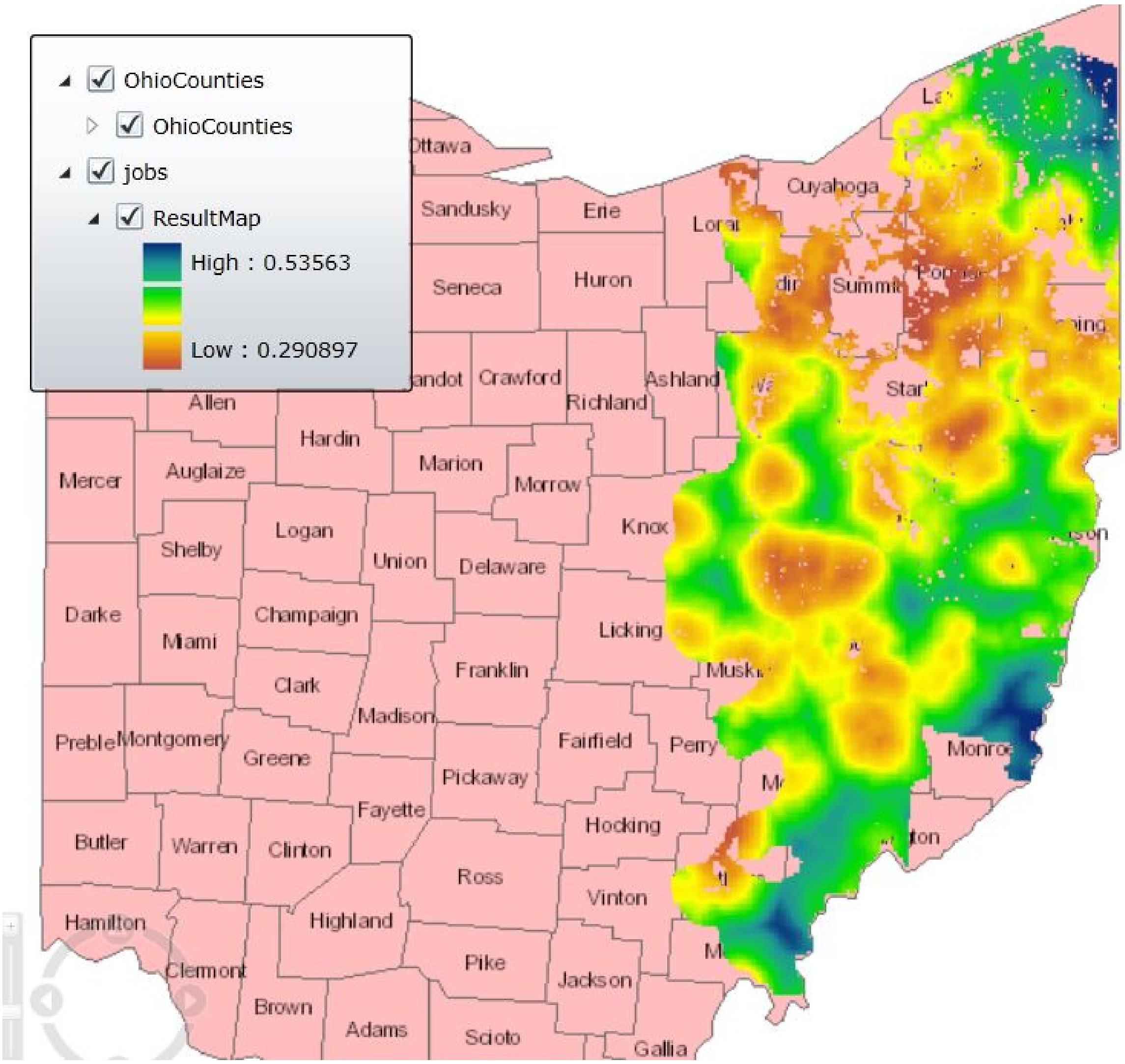

Figure 9. Example of a decision map

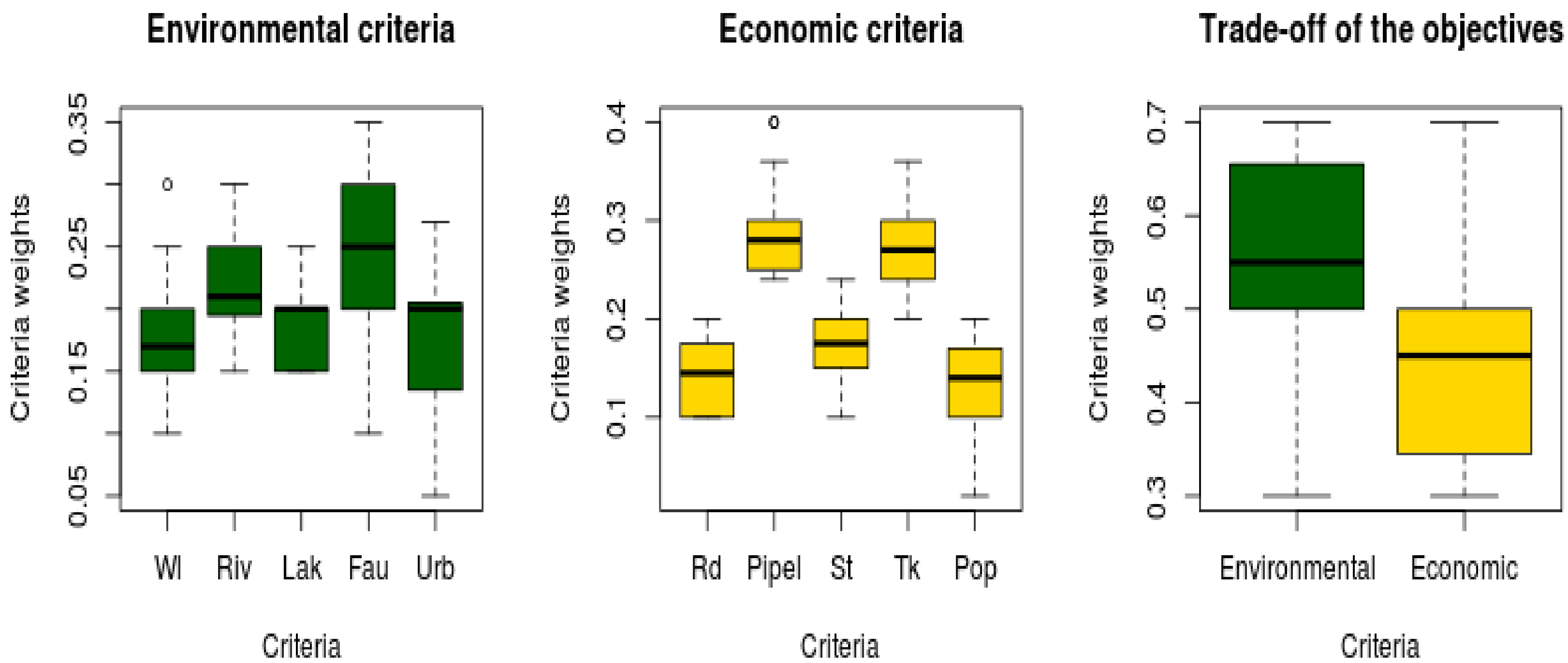

Figure 10. Distribution of weights assigned by the users for the environmental factors, the economic factors, and for the objectives.

APPENDIX B: TABLES

Table1. Fuzzy set memberships and membership functions

Objectives/Criteria	Control Point a	Control Point b	Fuzzy Membership
Environmental Criteria			
Distance to Wildlife Habitat (m)	1000	3000	Linear -increasing
Distance to Rivers (m)	600	3000	Linear -increasing
Distance to Lakes (m)	600	3000	Linear -increasing
Distance to Faults (m)	10000	30000	Linear -increasing
Distance to Urban (m)	1000	10000	Linear -increasing
Economic Criteria			
Proximity to road (m)	1000	3000	Linear-decreasing
Proximity to Pipelines (m)	1000	10000	Linear-decreasing
Proximity to Storage Area (m)	1000	10000	Linear-decreasing
Marcellus Shale Thickness (m)	0	28	Linear-increasing
Proximity to Population Density (km^2)	20	200	Linear-increasing

APPENDIX C: CODE

1. Xaml code for the map display

```
<UserControl x:Class="SDSS.MainPage"
    xmlns="http://schemas.microsoft.com/winfx/2006/xaml/presentation"
    xmlns:x="http://schemas.microsoft.com/winfx/2006/xaml"
    xmlns:d="http://schemas.microsoft.com/expression/blend/2008"
    xmlns:mc="http://schemas.openxmlformats.org/markup-
compatibility/2006"
    xmlns:esri="http://schemas.esri.com/arcgis/client/2009"
    xmlns:nav = "clr-
namespace:System.Windows.Controls;assembly=System.Windows.Controls.Navig
ation" >


    <Grid x:Name="LayoutRoot"
MouseLeftButtonDown="MainPage_MouseLeftButtonDown"
MouseLeftButtonUp="MainPage_MouseLeftButtonUp"
MouseMove="MainPage_MouseMove">

        <esri:Map x:Name="MyMap" Extent="-10120000,4700000,-
8168000,5300000">
            <esri:ArcGISTiledMapServiceLayer ID="Backgroud Layer"

Url="http://services.arcgisonline.com/ArcGIS/rest/services/World_Street_
Map/MapServer" />
            <esri:ArcGISDynamicMapServiceLayer ID="Ohio Counties"

Url="http://localhost:6080/arcgis/rest/services/Maps/OhioCounties/MapSer
ver"/>
            <esri:GroupLayer ID="Constraints">
                <esri:ArcGISDynamicMapServiceLayer  ID="National Parks
Forest"

Url="http://localhost:6080/arcgis/rest/services/Maps/NationalPark_Forest
/MapServer" />
                <esri:ArcGISDynamicMapServiceLayer  ID="Wetlands"
Opacity="0.4" Visible="True"
```

```
Url="http://localhost:6080/arcgis/rest/services/Maps/Wetland/MapServer"
/>
                <esri:ArcGISDynamicMapServiceLayer  ID="Urban Areas"
Opacity="0.4" Visible="True"

Url="http://localhost:6080/arcgis/rest/services/Maps/UrbanArea/MapServer
" />
            </esri:GroupLayer>

            <esri:GroupLayer ID="Environmental Consideration">
                <esri:ArcGISDynamicMapServiceLayer  ID="Wildelife
Habitat"

Url="http://localhost:6080/arcgis/rest/services/Maps/WildlifeHabitat/Map
Server" />
                <esri:ArcGISDynamicMapServiceLayer  ID="Rivers"
Opacity="0.4" Visible="True"
                Url=
"http://localhost:6080/arcgis/rest/services/Maps/Rivers/MapServer"/>
                <esri:ArcGISDynamicMapServiceLayer  ID="Lakes"

Url="http://localhost:6080/arcgis/rest/services/Maps/Lakes/MapServer" />
                <esri:ArcGISDynamicMapServiceLayer  ID="Faults "
Opacity="0.4" Visible="True"
                Url=
"http://localhost:6080/arcgis/rest/services/Maps/Faults/MapServer"/>
                <esri:ArcGISDynamicMapServiceLayer  ID="Urban Areas"
Visible="False"

Url="http://localhost:6080/arcgis/rest/services/Maps/UrbanArea/MapServer
" />
            </esri:GroupLayer>

            <esri:GroupLayer ID="Economic Consideration">
                <esri:ArcGISDynamicMapServiceLayer  ID="Marcellus Shale
Thickness" Visible="False"
                Url="
      http://localhost:6080/arcgis/rest/services/Maps/MarcellusShaleThic
kness/MapServer" />
```

```
                <esri:ArcGISDynamicMapServiceLayer  ID="Population 
Density" Opacity="0.4" Visible="False"
                Url= "
      http://localhost:6080/arcgis/rest/services/Maps/PopulationDensity/
MapServer"/>
                <esri:ArcGISDynamicMapServiceLayer  ID="Pipeline"
                Url="
http://localhost:6080/arcgis/rest/services/Maps/Pipeline/MapServer" />
                <esri:ArcGISDynamicMapServiceLayer  ID="Storage Area"
Opacity="0.4" Visible="True"
                Url=
"http://localhost:6080/arcgis/rest/services/Maps/StorageArea/MapServer"/>
                <esri:ArcGISDynamicMapServiceLayer  ID="Road"
Visible="False"

Url="http://localhost:6080/arcgis/rest/services/Maps/Roads/MapServer"/>
            </esri:GroupLayer>
        </esri:Map>

    </Grid>

            <esri:ScaleLine Map="{Binding ElementName=MyMap}"
Margin="10" HorizontalAlignment="Center" VerticalAlignment="Bottom" />
            <esri:Navigation Margin="300,2,2,2"
HorizontalAlignment="Left" VerticalAlignment="Bottom"
                         Map="{Binding ElementName=MyMap}">
            </esri:Navigation>

            <Grid HorizontalAlignment="Left" VerticalAlignment="Top" >
                <StackPanel Orientation="Vertical"
HorizontalAlignment="Left" Margin="0,0,0,0">
                    <Border BorderBrush="LightBlue" BorderThickness="1"
/>

                    <esri:Legend Name="MyMapLegend" Map="{Binding
ElementName=MyMap}" LayerItemsMode="Tree"
                         ShowOnlyVisibleLayers="False"
Refreshed="Legend_Refreshed"
                         HorizontalAlignment="Left"
VerticalAlignment="Center" MinHeight="2"  MinWidth="200" MaxWidth="250"
```

```
                        Margin="5,0,0,0" BorderBrush="Black">

                       <esri:Legend.MapLayerTemplate>
                           <DataTemplate>
                               <StackPanel Orientation="Horizontal">
                                   <CheckBox Content="{Binding Label}"
                                               IsChecked="{Binding
IsEnabled, Mode=TwoWay}"
                                               IsEnabled="{Binding
IsInScaleRange}" >
                                   </CheckBox>
                               </StackPanel>
                           </DataTemplate>
                       </esri:Legend.MapLayerTemplate>
                       <esri:Legend.LayerTemplate>
                           <DataTemplate>
                               <CheckBox Content="{Binding Label}"
                                 IsChecked="{Binding IsEnabled,
Mode=TwoWay}"
                                   IsEnabled="{Binding
IsInScaleRange}" >
                               </CheckBox>
                           </DataTemplate>
                       </esri:Legend.LayerTemplate>
                   </esri:Legend>
               </StackPanel>
           </Grid>

</UserControl>
```

2. VB code behind the SDSS tool interface

```
Private Sub CreateConstraints_Click(ByVal sender As Object, ByVal e As
RoutedEventArgs)
        'myPopupConstraints.IsOpen = False
        MyMap.Layers.Clear()
                Dim newOhioCounties As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
```

```
        newOhioCounties.Url =
"http://localhost:6080/arcgis/rest/services/Maps/OhioCounties/MapServer"
        MyMap.Layers.Add(newOhioCounties)
        Dim Union As New ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        Union.Url =
"http://localhost:6080/arcgis/rest/services/Maps/Union3/MapServer"
        Dim NationalParksForest As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        NationalParksForest.Url =
"http://localhost:6080/arcgis/rest/services/Maps/NationalPark_Forest/Map
Server"
        Dim Wetlands As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        Wetlands.Url =
"http://localhost:6080/arcgis/rest/services/Maps/Wetland/MapServer"
        Dim UrbanAreas As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        UrbanAreas.Url =
"http://localhost:6080/arcgis/rest/services/Maps/UrbanArea/MapServer"
        Dim NationalPark_Wetland As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        NationalPark_Wetland.Url =
"http://localhost:6080/arcgis/rest/services/Maps/Park_Wetland/MapServer"
        Dim NationalParks_UrbanAreas As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        NationalParks_UrbanAreas.Url =
"http://localhost:6080/arcgis/rest/services/Maps/NationalPark_Urban/MapS
erver"
        Dim Wetland_UrbanAreas As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        Wetland_UrbanAreas.Url =
"http://localhost:6080/arcgis/rest/services/Maps/Wetland_Urban/MapServer
"
        If Cbx1.IsChecked Then
            If Cbx2.IsChecked Then
                If Cbx3.IsChecked Then
                    MyMap.Layers.Clear()
                    MyMap.Layers.Add(newOhioCounties)
                    MyMap.Layers.Add(Union)
                ElseIf Cbx3.IsChecked = False Then
```

```
                MyMap.Layers.Clear()
                MyMap.Layers.Add(newOhioCounties)
                MyMap.Layers.Add(NationalPark_Wetland)
            End If
        ElseIf Cbx2.IsChecked = False Then
            If Cbx3.IsChecked Then
                MyMap.Layers.Clear()
                MyMap.Layers.Add(newOhioCounties)
                MyMap.Layers.Add(NationalParks_UrbanAreas)
            ElseIf Cbx3.IsChecked = False Then
                MyMap.Layers.Clear()
                MyMap.Layers.Add(newOhioCounties)
                MyMap.Layers.Add(NationalParksForest)
            End If
        End If
    ElseIf Cbx1.IsChecked = False Then
        If Cbx2.IsChecked Then
            If Cbx3.IsChecked Then
                MyMap.Layers.Clear()
                MyMap.Layers.Add(newOhioCounties)
                MyMap.Layers.Add(Wetland_UrbanAreas)
            ElseIf Cbx3.IsChecked = False Then
                MyMap.Layers.Clear()
                MyMap.Layers.Add(newOhioCounties)
                MyMap.Layers.Add(Wetlands)
            End If
        ElseIf Cbx2.IsChecked = False Then
            If Cbx3.IsChecked Then
                MyMap.Layers.Clear()
                MyMap.Layers.Add(newOhioCounties)
                MyMap.Layers.Add(UrbanAreas)
            ElseIf Cbx3.IsChecked = False Then
                MyMap.Layers.Clear()
                MyMap.Layers.Add(newOhioCounties)
            End If
        End If
    End If
End Sub
'This NextConstraint is used for open the Environmental criteria
page
```

```
    Private Sub ConstraintNext_Click(ByVal sender As Object, ByVal e As
RoutedEventArgs)
        IsTabStop = "True"
        TabIndex = "0"
        myPopupConstraints.IsOpen = False
        myPopupEnv.IsOpen = True
    End Sub

    'This EnvPrevious_Click is used for going back to constraints page
from environmental page
    Private Sub EnvPrevious_Click(ByVal sender As Object, ByVal e As
RoutedEventArgs)
        myPopupConstraints.IsOpen = True
        myPopupEnv.IsOpen = False
    End Sub

    'This EnvNext_Click is used for going to Economic page from
environmental page
    Private Sub EnvNext_Click(ByVal sender As Object, ByVal e As
RoutedEventArgs)
        'The following part is to set the sum of the textbox values to 1,
otherwise will prompt an error message
        Dim value4 As Double = CDbl(Chx4TextBox.Text)
        Dim value5 As Double = CDbl(Chx5TextBox.Text)
        Dim value6 As Double = CDbl(Chx6TextBox.Text)
        Dim value7 As Double = CDbl(Chx7TextBox.Text)
        Dim value8 As Double = CDbl(Chx8TextBox.Text)
        If Cbx4.IsChecked = False Then
            value4 = 0.0
        End If
        If Cbx5.IsChecked = False Then
            value5 = 0.0
        End If
        If Cbx6.IsChecked = False Then
            value6 = 0.0
        End If
        If Cbx7.IsChecked = False Then
            value7 = 0.0
        End If
        If Cbx8.IsChecked = False Then
```

```
            value8 = 0.0
        End If
        If (value4 + value5 + value6 + value7 + value8) <> 1.0 Then
            MessageBox.Show("Please make sure all the values sum up to
1", "Please sum up to 1", MessageBoxButton.OK)
            myPopupEco.IsOpen = False
            myPopupEnv.IsOpen = True
        ElseIf (value4 + value5 + value6 + value7 + value8) = 1.0 Then
            myPopupEco.IsOpen = True
            myPopupEnv.IsOpen = False
        End If
        'The following part is to send the user input information to the
PostgreSQL database

        Dim Envservice As New EnvServiceClient()
        Envservice.EnvInsertDataAsync(value4, value5, value6, value7,
value8)

    End Sub
    'This EnvPrevious_Click is used for going back to constraints page
from environmental page
    Private Sub EcoPrevious_Click(ByVal sender As Object, ByVal e As
RoutedEventArgs)
        myPopupEco.IsOpen = False
        myPopupEnv.IsOpen = True
    End Sub
    'This EnvNext_Click is used for going to Economic page from
environmental page
    Private Sub EcoNext_Click(ByVal sender As Object, ByVal e As
RoutedEventArgs)
        Dim value9 As Double = CDbl(Chx9TextBox.Text)
        Dim value10 As Double = CDbl(Chx10TextBox.Text)
        Dim value11 As Double = CDbl(Chx11TextBox.Text)
        Dim value12 As Double = CDbl(Chx12TextBox.Text)
        Dim value13 As Double = CDbl(Chx13TextBox.Text)
        If Cbx9.IsChecked = False Then
            value9 = 0.0
        End If
        If Cbx10.IsChecked = False Then
            value10 = 0.0
```

```
        End If
        If Cbx11.IsChecked = False Then
            value11 = 0.0
        End If
        If Cbx12.IsChecked = False Then
            value12 = 0.0
        End If
        If Cbx13.IsChecked = False Then
            value13 = 0.0
        End If
        Dim total As Double = value9 + value10 + value11 + value12 +
value13
        If (value9 + value10 + value11 + value12 + value13) <> 1.0 Then
            'MessageBox.Show("Please make sure all the values sum up to
1", "Please sum up to 1", MessageBoxButton.OK)
            MessageBox.Show("Please make sure all the values sum up to
1" + total.ToString, "Please sum up to 1", MessageBoxButton.OK)
            myPopupEco.IsOpen = True
            myPopupBalance.IsOpen = False
        ElseIf (value9 + value10 + value11 + value12 + value13) = 1.0
Then
            myPopupEco.IsOpen = False
            myPopupBalance.IsOpen = True
        End If

        ' This is used for storing data from users' input to the
database
        Dim Ecoservice As New EcoServiceClient()
        Ecoservice.EcoInsertDataAsync(value9, value10, value11, value12,
value13)
    End Sub
    'This EnvPrevious_Click is used for going back to constraints page
from environmental page
    Private Sub BalanPrevious_Click(ByVal sender As Object, ByVal e As
RoutedEventArgs)
        myPopupEco.IsOpen = True
        myPopupBalance.IsOpen = False
    End Sub
```

```
    ' This Balance_ValueChanged is used for displaying the values of the
two criteria  b
    Private Sub Balance_ValueChanged(ByVal sender As Object, ByVal e As
RoutedPropertyChangedEventArgs(Of Double))
        Dim seconds As Integer = Convert.ToInt32(e.NewValue)
        SliderLeftVal.Text = String.Format(100 - seconds)
        SliderRightVal.Text = String.Format(seconds)
    End Sub

    Private Sub DisplayConstraintMaps_Click(sender As System.Object, e
As System.Windows.RoutedEventArgs)
        MyMap.Layers.Clear()
        Dim newOhioCounties As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        newOhioCounties.Url =
"http://localhost:6080/arcgis/rest/services/DataLayers/OhioCounties/MapS
erver"
        MyMap.Layers.Add(newOhioCounties)
        Dim NationalParksForest As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        NationalParksForest.Url =
"http://localhost:6080/arcgis/rest/services/Maps/NationalPark_Forest/Map
Server"
        MyMap.Layers.Add(NationalParksForest)
        Dim Wetlands As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        Wetlands.Url = "
      http://localhost:6080/arcgis/rest/services/Maps/Wetland/MapServer"
        MyMap.Layers.Add(Wetlands)
        Dim UrbanAreas As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        UrbanAreas.Url =
"http://localhost:6080/arcgis/rest/services/Maps/UrbanArea/MapServer"
        MyMap.Layers.Add(UrbanAreas)
    End Sub
    Private Sub CloseConstraints_Click(sender As System.Object, e As
System.Windows.RoutedEventArgs)
        myPopupConstraints.IsOpen = False
    End Sub
```

```
    Private Sub CloseEnv_Click(sender As System.Object, e As
System.Windows.RoutedEventArgs)
        myPopupEnv.IsOpen = False
    End Sub
    Private Sub CloseEco_Click(sender As System.Object, e As
System.Windows.RoutedEventArgs)
        myPopupEco.IsOpen = False
    End Sub
    Private Sub CloseBal_Click(sender As System.Object, e As
System.Windows.RoutedEventArgs)
        myPopupBalance.IsOpen = False
    End Sub
    'This DisplayAllMaps_Click is to display all the map layers
    Private Sub DisplayAllMaps_Click(sender As System.Object, e As
System.Windows.RoutedEventArgs)
        MyMap.Layers.Clear()
        If myPopupConstraints.IsOpen = True Then
            Dim newOhioCounties As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            newOhioCounties.Url =
"http://localhost:6080/arcgis/rest/services/DataLayers/OhioCounties/MapS
erver"
            MyMap.Layers.Add(newOhioCounties)
            Dim NationalParksForest As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            NationalParksForest.Url =
"http://localhost:6080/arcgis/rest/services/Maps/NationalPark_Forest/Map
Server"
            MyMap.Layers.Add(NationalParksForest)
            Dim Wetlands As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            Wetlands.Url = "
      http://localhost:6080/arcgis/rest/services/Maps/Wetland/MapServer"
            MyMap.Layers.Add(Wetlands)
            Dim UrbanAreas As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            UrbanAreas.Url =
"http://localhost:6080/arcgis/rest/services/Maps/UrbanArea/MapServer"
            MyMap.Layers.Add(UrbanAreas)
        End If
```

```
        If myPopupEnv.IsOpen = True Then
            Dim newOhioCounties As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            newOhioCounties.Url =
"http://localhost:6080/arcgis/rest/services/DataLayers/OhioCounties/MapS
erver"
            MyMap.Layers.Add(newOhioCounties)
            Dim newWildlifeHab As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            newWildlifeHab.Url = "
      http://localhost:6080/arcgis/rest/services/Maps/WildlifeHabitat/Ma
pServer"
            MyMap.Layers.Add(newWildlifeHab)
            Dim newRiver As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            newRiver.Url = "
      http://localhost:6080/arcgis/rest/services/Maps/Rivers/MapServer"
            MyMap.Layers.Add(newRiver)
            Dim newLake As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            newLake.Url = "
      http://localhost:6080/arcgis/rest/services/Maps/Lakes/MapServer"
            MyMap.Layers.Add(newLake)
            Dim newFault As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            newFault.Url = "
      http://localhost:6080/arcgis/rest/services/Maps/Faults/MapServer"
            MyMap.Layers.Add(newFault)
            Dim newUrban As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            newUrban.Url =
"http://localhost:6080/arcgis/rest/services/Maps/UrbanArea/MapServer"
            MyMap.Layers.Add(newUrban)
        End If
        If myPopupEco.IsOpen = True Then
            Dim newOhioCounties As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            newOhioCounties.Url =
"http://localhost:6080/arcgis/rest/services/DataLayers/OhioCounties/MapS
erver"
```

```
            MyMap.Layers.Add(newOhioCounties)
            Dim MarceThickness As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            MarceThickness.Url =
"http://localhost:6080/arcgis/rest/services/Maps/MarcellusShaleThickness
/MapServer"
            MyMap.Layers.Add(MarceThickness)
            Dim PopulationDensity As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            PopulationDensity.Url =
"http://localhost:6080/arcgis/rest/services/Maps/PopulationDensity/MapSe
rver"
            MyMap.Layers.Add(PopulationDensity)
            Dim Road As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            Road.Url =
"http://localhost:6080/arcgis/rest/services/Maps/Roads/MapServer"
            MyMap.Layers.Add(Road)
            Dim Pipeline As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            Pipeline.Url = "
http://localhost:6080/arcgis/rest/services/Maps/Pipeline/MapServer"
            MyMap.Layers.Add(Pipeline)
            Dim StorageArea As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
            StorageArea.Url =
"http://localhost:6080/arcgis/rest/services/Maps/StorageArea/MapServer"
            MyMap.Layers.Add(StorageArea)
        End If
    End Sub

    Private Sub DisplayEnvMaps_Click(sender As System.Object, e As
System.Windows.RoutedEventArgs)
        MyMap.Layers.Clear()
        Dim newOhioCounties As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        newOhioCounties.Url =
"http://localhost:6080/arcgis/rest/services/DataLayers/OhioCounties/MapS
erver"
        MyMap.Layers.Add(newOhioCounties)
```

```
        Dim newWildlifeHab As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        newWildlifeHab.Url = "
      http://localhost:6080/arcgis/rest/services/Maps/WildlifeHabitat/Ma
pServer"
        MyMap.Layers.Add(newWildlifeHab)
        Dim newRiver As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        newRiver.Url = "
      http://localhost:6080/arcgis/rest/services/Maps/Rivers/MapServer"
        MyMap.Layers.Add(newRiver)
        Dim newLake As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        newLake.Url = "
      http://localhost:6080/arcgis/rest/services/Maps/Lakes/MapServer"
        MyMap.Layers.Add(newLake)
        Dim newFault As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        newFault.Url = "
      http://localhost:6080/arcgis/rest/services/Maps/Faults/MapServer"
        MyMap.Layers.Add(newFault)
        Dim newUrban As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        newUrban.Url =
"http://localhost:6080/arcgis/rest/services/Maps/UrbanArea/MapServer"
        MyMap.Layers.Add(newUrban)
    End Sub

    Private Sub DisplayEcoMaps_Click(sender As System.Object, e As
System.Windows.RoutedEventArgs)
        MyMap.Layers.Clear()
        Dim newOhioCounties As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        newOhioCounties.Url =
"http://localhost:6080/arcgis/rest/services/DataLayers/OhioCounties/MapS
erver"
        MyMap.Layers.Add(newOhioCounties)
        Dim MarceThickness As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
```

```
        MarceThickness.Url =
"http://localhost:6080/arcgis/rest/services/Maps/MarcellusShaleThickness
/MapServer"
        MyMap.Layers.Add(MarceThickness)
        Dim PopulationDensity As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        PopulationDensity.Url =
"http://localhost:6080/arcgis/rest/services/Maps/PopulationDensity/MapSe
rver"
        MyMap.Layers.Add(PopulationDensity)
        Dim Road As New ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        Road.Url =
"http://localhost:6080/arcgis/rest/services/Maps/Roads/MapServer"
        MyMap.Layers.Add(Road)
        Dim Pipeline As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        Pipeline.Url = "
http://localhost:6080/arcgis/rest/services/Maps/Pipeline/MapServer"
        MyMap.Layers.Add(Pipeline)
        Dim StorageArea As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        StorageArea.Url =
"http://localhost:6080/arcgis/rest/services/Maps/StorageArea/MapServer"
        MyMap.Layers.Add(StorageArea)
    End Sub
End Class
```

3. VB code for geo-processing task

```
Private Sub SubmitJob()

        myPopupBalance.IsOpen = False
        MyMap.Layers.Clear()
        Dim newOhioCounties As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer
        newOhioCounties.Url =
"http://localhost:6080/arcgis/rest/services/Maps/OhioCounties/MapServer"
        MyMap.Layers.Add(newOhioCounties)

        Dim parameters As New List(Of GPParameter)()
```

```
        parameters.Add(New GPDouble("WildValue", CDbl(Chx4TextBox.Text)))
        parameters.Add(New GPDouble("RiverValue",
CDbl(Chx5TextBox.Text)))
        parameters.Add(New GPDouble("LakeValue", CDbl(Chx6TextBox.Text)))
        parameters.Add(New GPDouble("FaultValue",
CDbl(Chx7TextBox.Text)))
        parameters.Add(New GPDouble("UrbanValue",
CDbl(Chx8TextBox.Text)))
        parameters.Add(New GPDouble("RoadValue", CDbl(Chx9TextBox.Text)))
        parameters.Add(New GPDouble("PipeValue",
CDbl(Chx10TextBox.Text)))
        parameters.Add(New GPDouble("StorageValue",
CDbl(Chx11TextBox.Text)))
        parameters.Add(New GPDouble("MarcValue",
CDbl(Chx12TextBox.Text)))
        parameters.Add(New GPDouble("PopDenValue",
CDbl(Chx13TextBox.Text)))

        parameters.Add(New GPDouble("EnvValue",
((CDbl(SliderLeftVal.Text)) / 100)))
        parameters.Add(New GPDouble("EcoValue",
((CDbl(SliderRightVal.Text)) / 100)))

        If Cbx1.IsChecked Then
            If Cbx2.IsChecked Then
                If Cbx3.IsChecked Then
                    _geoprocessorTask = New
Geoprocessor("http://localhost:6080/arcgis/rest/services/Services/SDSS15
/GPServer/SDSS15")
                ElseIf Cbx3.IsChecked = False Then

                    _geoprocessorTask = New
Geoprocessor("http://localhost:6080/arcgis/rest/services/GPServices/SDSS
2/GPServer/SDSS2")
                End If
            ElseIf Cbx2.IsChecked = False Then
                If Cbx3.IsChecked Then
                    _geoprocessorTask = New
Geoprocessor("http://localhost:6080/arcgis/rest/services/GPServices/SDSS
3/GPServer/SDSS3")
```

```
                ElseIf Cbx3.IsChecked = False Then
                    _geoprocessorTask = New
Geoprocessor("http://localhost:6080/arcgis/rest/services/GPServices/SDSS
4/GPServer/SDSS4")
                End If
            End If
        ElseIf Cbx1.IsChecked = False Then
            If Cbx2.IsChecked Then
                If Cbx3.IsChecked Then
                    _geoprocessorTask = New
Geoprocessor("http://localhost:6080/arcgis/rest/services/GPServices/SDSS
5/GPServer/SDSS5")
                ElseIf Cbx3.IsChecked = False Then
                    _geoprocessorTask = New
Geoprocessor("http://localhost:6080/arcgis/rest/services/GPServices/SDSS
6/GPServer/SDSS6")
                End If
            ElseIf Cbx2.IsChecked = False Then
                If Cbx3.IsChecked Then
                    _geoprocessorTask = New
Geoprocessor("http://localhost:6080/arcgis/rest/services/GPServices/SDSS
7/GPServer/SDSS7")
                ElseIf Cbx3.IsChecked = False Then
                    _geoprocessorTask = New
Geoprocessor("http://localhost:6080/arcgis/rest/services/GPServices/SDSS
8/GPServer/SDSS8")
                End If
            End If
        End If

        AddHandler _geoprocessorTask.JobCompleted, AddressOf
GeoprocessorTask_JobCompleted
        AddHandler _geoprocessorTask.Failed, AddressOf
GeoprocessorTask_Failed
        AddHandler _geoprocessorTask.StatusUpdated, AddressOf
GeoprocessorTask_StatusUpdated
        _geoprocessorTask.OutputSpatialReference =
MyMap.SpatialReference
        _geoprocessorTask.SubmitJobAsync(parameters)
        _geoprocessorTask.UpdateDelay = 1000000
```

```
    End Sub

    Private Sub GeoprocessorTask_StatusUpdated(sender As Object, e As
JobInfoEventArgs)
        MessageBox.Show("The decision making process is busy with
creating final decision map. Please wait ......")

        jobid = If(e.JobInfo.JobStatus = esriJobStatus.esriJobCancelled
OrElse e.JobInfo.JobStatus = esriJobStatus.esriJobDeleted OrElse
e.JobInfo.JobStatus = esriJobStatus.esriJobFailed, Nothing,
e.JobInfo.JobId)
        If e.JobInfo.JobStatus = esriJobStatus.esriJobCancelling Then
            SubmitJob()
        End If
    End Sub
    Private Sub GeoprocessorTask_JobCompleted(ByVal sender As Object,
ByVal e As JobInfoEventArgs)
        jobid = Nothing
        MessageBox.Show("The final decision map is ready for
displaying!")
        If e.JobInfo.JobStatus = esriJobStatus.esriJobSucceeded Then
            _geoprocessorTask.GetResultDataAsync(e.JobInfo.JobId,
"ResultMap")
        End If

        Dim resultLayer As New
ESRI.ArcGIS.Client.ArcGISDynamicMapServiceLayer

        If Cbx1.IsChecked Then
            If Cbx2.IsChecked Then
                If Cbx3.IsChecked Then
                    resultLayer.Url =
"http://localhost:6080/arcgis/rest/services/Services/SDSS15/MapServer/jo
bs/" + e.JobInfo.JobId

                ElseIf Cbx3.IsChecked = False Then
                    resultLayer.Url =
"http://localhost:6080/arcgis/rest/services/GPServices/SDSS2/MapServer/j
obs/" + e.JobInfo.JobId
```

```
                End If
            ElseIf Cbx2.IsChecked = False Then
                If Cbx3.IsChecked Then
                    resultLayer.Url =
"http://localhost:6080/arcgis/rest/services/GPServices/SDSS3/MapServer/j
obs/" + e.JobInfo.JobId
                ElseIf Cbx3.IsChecked = False Then
                    resultLayer.Url =
"http://localhost:6080/arcgis/rest/services/GPServices/SDSS4/MapServer/j
obs/" + e.JobInfo.JobId
                End If
            End If
        ElseIf Cbx1.IsChecked = False Then
            If Cbx2.IsChecked Then
                If Cbx3.IsChecked Then
                    resultLayer.Url =
"http://localhost:6080/arcgis/rest/services/GPServices/SDSS5/MapServer/j
obs/" + e.JobInfo.JobId
                ElseIf Cbx3.IsChecked = False Then
                    resultLayer.Url =
"http://localhost:6080/arcgis/rest/services/GPServices/SDSS6/MapServer/j
obs/" + e.JobInfo.JobId
                End If
            ElseIf Cbx2.IsChecked = False Then
                If Cbx3.IsChecked Then
                    resultLayer.Url =
"http://localhost:6080/arcgis/rest/services/GPServices/SDSS7/MapServer/j
obs/" + e.JobInfo.JobId
                ElseIf Cbx3.IsChecked = False Then
                    resultLayer.Url =
"http://localhost:6080/arcgis/rest/services/GPServices/SDSS8/MapServer/j
obs/" + e.JobInfo.JobId
                End If
            End If
        End If

        MyMap.Layers.Add(resultLayer)
    End Sub
    Private Sub GeoprocessorTask_Failed(ByVal sender As Object, ByVal e
As TaskFailedEventArgs)
```

```
        MessageBox.Show("Geoprocessor service failed: " &
e.Error.Message)
    End Sub

    'This EnvNext_Click is used for going to Economic page from
environmental page
    Private Sub Submit_Click(ByVal sender As Object, ByVal e As
RoutedEventArgs)
        myPopupBalance.IsOpen = False

        'This is used for storing the values for both environmental
criteria and economic criteria into the DB
        Dim ValueEnv As Double = CDbl(SliderLeftVal.Text) / 100
        Dim ValueEco As Double = CDbl(SliderRightVal.Text) / 100

        Dim TradeService As New TradeServiceClient()
        TradeService.TradeInsertDataAsync(ValueEnv, ValueEco)

        SubmitJob()
    End Sub
```