A SPATIAL DECISION SUPPORT SYSTEM FOR ECONOMIC ANALYSIS OF SEDIMENT CONTROL ON RANGELAND WATERSHEDS

by

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ABSTRACT

Spatial decision support systems (SDSS) integrate the state of the art technology, such as GIS, database and distributed models into decision support systems to support geospatial analysis that is particularly useful for watershed management, such as TMDL development on watersheds required by the Clean Water Act. This dissertation focuses on the development of a SDSS to assess the economic and environmental impacts from various best management practices (BMPs) in reducing sediment yield on rangeland watersheds.

The SDSS included three major parts: the models, database and web-based interfaces. The model part is the core of the SDSS that provides the functionality of watershed economic analysis. The model maximized the profit of a representative ranch assumed to cover the whole watershed with the constraints of production technology, resource, sediment control objectives and sustainable utilization. A watershed was spatially segmented into basic units, each unit with similar plant growth and forage utilization. There are two major types of models, static and dynamic. Each model type supported variations in plant growth, grazing and ranch operations. Upland erosion was estimated through RUSLE2 and the sediment yield of a watershed was estimated from upland erosion and sediment delivery ratios for each basic unit. GAMS programs were used to solve the optimization models. The SDSS provides a platform to automatically implement the models. The database was the major tool in managing spatial and non-spatial data. A series of customized web pages were developed to support users' inputs,

watershed analysis and result visualization. The embedded procedures were integrated into the SDSS to support analytical functionality, including geospatial analysis, model parameterization and web page generation.

The SDSS was used to assess sediment control on the Walnut Gulch Experimental Watershed. The SDSS was parameterized primarily using publicly available data and a preliminary validation was made. The SDSS functionality was illustrated through eight applications. The results showed that given recent prices, new infrastructure practices would cause a financial burden to ranches. Better grazing management may provide an economic alternative to meet the sediment control objective and cost sharing could provide ranchers the incentives to participate in conservation plans.

CHAPTER 1 INTRODUCTION

The Clean Water Act (CWA) requires states to identify water bodies that do not meet water quality standards and to develop total maximum daily load (TMDL) plans for cleaning them up. A TMDL needs to identify all the pollution sources, define a safe load capacity, and allocate the capacities to different polluters to ensure the waters meet the environmental standards (EPA, 1999).

TMDLs are defined on a watershed level. A watershed is a hydrological unit where all runoff flows into a same outlet. This property makes watersheds the natural unit to control water quality. A watershed is a composite of different landscapes and land uses. The diversity of land use and ownership on a watershed requires that decision makers consider several factors, such as technology, economics and politics, in TMDL design.

With decades of efforts on control of point source pollution, nonpoint source (NPS) pollution has become the largest sources of water pollution for impaired water bodies (Boyd, 2000a; EPA, 2000). Sediment is one of the major NPS pollutants and it is also the transport medium of many other pollutants (EPA, 2004).

NPS problems vary in spatial and temporal dimensions (Braden and Segerson, 1993). TMDL regulations provide flexibility to adapt control objectives and schemes to special local environmental and economic condition (Boyd, 2000b). Each TMDL may have its own environmental objective and allocation mechanism. There are different policy instruments to deal with NPS control. For problems of sediment control on surface waters, emission and management practices have a high rank based on three criteria: ability to rank, enforcement and correlation with water quality, among five policy instruments proposed by Braden and Segerson (1993).

Varieties of best management practices (BMPs) were developed for sediment control on different land use types. Government agencies developed a series of BMP guides to help farmers and ranchers to implement these practices. The NRCS, formerly the Soil Conservation Service (SCS), is a major government agency offering technical aids in soil conservation practices for agricultural activities. More description of these standards can be found seen through NRCS websites (NRCS, 2004). Other federal agencies, Bureau of Land Management (BLM), and the Forest Service of U.S. Department of Agriculture (USFS) also developed BMP guidelines for land management.

The selection of BMPs on a watershed level is a complex problem. Administrators and interest groups desire tools to aid in selecting BMPs for rangeland watershed to meet environmental objectives. This dissertation is intended to illustrate a prototype of such tool that can be used in developing TMDL on rangeland watershed with sediment problems.

1.1. Problem Statement

Rangeland is a major landscape in the western USA. Ranching is a traditional land use on western rangeland. Historic grazing over the West caused a series of problems, such as range ecosystem degradation, erosion and water quality problems (Jacobs, 1991). Sediment is one of the major pollutants from rangeland degradation. Economic development and increasing population impose more pressure for competition over scarce water resources in western rangeland. The need to implement TMDLs on rangeland is increasing.

Although federal agencies, such as NRCS, BLM, USFS, and many state agencies have developed BMPs for sediment and erosion control on rangeland, it is a challenging job to develop a TMDL for rangeland watersheds. Several reasons cause the difficulty of the selection. Firstly, the options of BMP practices in a watershed TMDL plan could be huge. There are many geographic locations in a watershed and each location may implement several BMPs. It is a challenging job to find the best solution among huge combinations. Secondly, the management-impact relationships for rangeland watershed system are generally complex. Most current system understanding is based on simplified relationships with great uncertainty.

Several interest groups are directly affected by TMDLs and/or other environmental regulations. State environmental quality agencies need to define and administer TMDL programs. The public land management agencies, such as BLM and USFS, need to adjust their management policy to meet environmental requirements. Consequently, ranchers using public lands need to adjust their managements to meet TMDL and other public land requirements. All these stakeholders are interested in several questions: What are the best technologies to control pollution? Where and how should the control practices be implemented? What is the best option among the alternatives in terms of environmental and economic impacts? How do policies affect the economic burden of different stakeholders?

To answer these questions, decision makers need an inter-disciplinary study which may include hydrology, biology, ecology, watershed management and many technologies of modeling and GIS. Biophysical models are important in understanding of management impact relationship of rangeland system (Carlson et al., 1993). Economics is also important in decision making for such management problems. The cost reduced through a cost effectiveness analysis of TMDL can be huge (EPA, 2001). Few managers can master all these skills. Fortunately, state-of-the-art technologies provide the most efficient way to transfer knowledge to decision maker. Thus, it is highly desirable to develop tools that use the state-of-the-art technology to help decision makers to solve their problems with least requirements of data, experiences and time.

Universities and research institutes have accumulated knowledge of rangeland processes in the format of theories, models and data. The knowledge provides better understanding of the complex relationships of rangeland processes. Transferring the knowledge to decision makers can be done through different approaches. Generally, users are concerned about the functionality, reliability and the accessibility. Many existing hydrological and erosion models focus on natural processes, and the economic component is omitted in most hydrological models. The omission of an economic component is reasonable for many hydrological studies. However, the economic factor is a necessary part for decision makers to rank different options. Because the possible economic and environmental impacts of watershed management may be huge, decision makers require robust approaches for their decisions. Furthermore, the scope of applications may be affected by many factors, such as costs, hardware, software and personal requirements. Any system must make tradeoffs among these factors. Fortunately, technology development provides a possibility to improve all these aspects.

In order to meet these requirements, this study develops a prototype web-based economic Spatial Decision Support System (SDSS) for rangeland watersheds. The SDSS is a tool to analyze sediment control problems on rangeland watersheds from an economic perspective. The system allows users to formulate their own problems, make analysis and visualize results through web browsers. The embedded models integrate major rangeland processes and are used to make complex analysis. Results from the SDSS provide useful information in developing TMDLs on rangeland watershed.

1.2. Objective

The overall objective of this dissertation is to develop a prototype spatial decision support system (SDSS) that can be used to assess the economics of sediment control on rangeland watershed through a web-based environment. The overall objective can be divided into several sub-objectives. Specifically, the sub-objectives of this dissertation include:

1) Develop integrated constrained optimization models that can simulate the bio-physical and production processes of range systems. The models should include the major processes of a ranch production system. The models can assess economic and environmental impacts of different management plans.

2) Develop a database to manage all the spatial and non-spatial data.

3) Develop a series of web page interfaces to help users create inputs, run models and view results.

4) Implement an SDSS to integrate database, models and interface in one system.

5) Apply the SDSS to a sample watershed and illustrate the functionality through a sample analysis.

The embedded models focus on grazing land management. Other land use types, such as urban areas, cropland and roads, may also contribute significantly to sediment loads to watershed outlets. These sediment sources are ignored. Sediment is the only pollutant considered. The BMPs considered in the models include fencing, water points, stock ponds and grazing intensity. The policies considered in the model include varying sediment yield control level and cost sharing of infrastructures.

1.3. Approach

This study consists of two major parts, the economic model development and the SDSS implementation. In the model development part, the focus is to develop the models of sediment control on rangeland watersheds. The problem is formulated as a representative ranch that can use all the pastures in a watershed. Ranch production is defined as a nonlinear optimization problem for maximizing profits. And the production functions are an integrated system of different components of range processes, including climate, plant production, livestock grazing, biomass conversion, erosion, herd conversion and economic valuation. Since most range processes are nonlinear, nonlinear functions are used in modeling. The spatial heterogeneity is addressed by dividing a watershed into 'basic units" with the similar plant community, grazing and erosion. Two types of models are used to solve different problems. A static model is used to address the long-term equilibrium relationship. A dynamic model is used to simulate the dynamic process of different managements. These models are coded in GAMS and are solved in GAMS NLP solvers.

The SDSS provides a user-friendly platform through efficient data management and integrated models. The SDSS uses a web service architecture as the framework and integrates several servers into one application system. The database management uses an

Oracle database server to manage all spatial and non-spatial sever. The interfaces include static web-pages as well as dynamic web-pages, map browser and editor to create customized web pages. The embedded models are controlled by the center server and are automatically implemented under users' requests. Users can creates inputs, run the models and view results through a web browser by clicking and typing.

1.4. Benefits

The study could provide an analytical tool for sediment control problems on rangeland watersheds. Several user groups may benefit from this study. Firstly, the study provides administrators the ability to evaluate policies for proper sediment control in a rangeland watershed. The SDSS can help to find the best solution from many management alternatives based on economic and economic criteria and assess the policy design that can provide incentives for ranchers to participate in a plan. Secondly, this study provides ranchers a tool to select the best management practices and find the most effective sites to implement the sediment control. Thirdly, the prototype of this SDSS provides a template that can be extended to other areas and add more functionality for this type of management problem. The EPA report (EPA, 2001) showed that cost-effective TMDL programs could save a median 75%, with a range of 21%-92%, for BOD and nutrient reduction programs. Although there is not a survey on cost reduction on rangeland watershed TMDL, the cost-saving potential could be large considering large investments on TMDL implementation.

In summary, the system may help different users to access analysis tools by reducing facility and human resource investments. Otherwise, they may not make these analyses because of the high cost. The web-based system can also accelerate the knowledge transfer from researcher to decision maker. The wide accessibility of the analysis tool will promote more efficient environment management.

1.5. Outline of the Dissertation

The dissertation consists of six chapters. The second chapter focuses on a comprehensive literature review on the topics that are closely related with this study. The third chapter describes the model development, including the economic theory, the model structure, the function for each component and the possible applications. The fourth chapter describes the SDSS system, including database design and implementation, interface design, analysis flow chart, system integration and functionality. The fifth chapter describes the implementation of the SDSS in Walnut Gulch Watershed and makes a sample analysis for this watershed. The sixth chapter summarizes the study and proposes the recommendations for the future study. Appendices include major parameters sources, program code and sample output results.

CHAPTER 2 LITERATURE REVIEW

Understanding the economics of sediment control on rangeland watersheds requires an interdisciplinary study. An effective study may need the knowledge of range management, economics, watershed management, ecology, operations research, information technology, etc. This chapter reviews three major topics that are related with this study. The first topic is modeling bio-physical processes of rangeland ecosystems. The second topic is the economics of range and watershed management. The third topic is the decision support systems (DSS) in natural resource management.

2.1. Rangeland Processes and Modeling

Understanding bio-physical processes in rangeland systems is critical for managing range resources. Rangeland systems consist of several major components, such as climate, soil, plant and animal. These components interact with each other through energy and matter exchange. However current knowledge of bio-physical processes in rangeland is still limited. Most existing quantitative relationships are empirical relationships that are valid only at certain conditions and for special sites. Simulation models are the major tools to study the quantitative relationships. This section reviews the literature of major components in rangeland ecosystem and the interactions among them.

Plant

In the western U.S., plant production data on public land have been collected through periodical field surveys. However, general quantitative relationships of plant growth and the impacts of grazing and erosion on rangeland productivity are still limited (Gifford and Whitehead 1982; Office of Technology Assessment, Congress of the United State, 1982).

Several factors are important in determining plant production. Precipitation is the most important factor affecting plant production in arid regions. Lane et al. (1984) studied the impacts of soil water in forage production. Other factors such as soil nutrients are also important in plant growth.

Several models were proposed to predict the plant production of rangeland. Kiniry et al (2002) developed a model that simulated the biomass production of different ecological sites. Uresk et al. (1975) derived an empirical relationship of growth curve of Blue Grama. SPUR is an integrated model with a plant component, which can simulate the growth of several species simultaneously.

Livestock

The livestock component includes several processes, such as forage intake, species selection, grazing distribution and livestock herd management. Forage intake is the process that livestock harvest and digest forage. The amount of forage intake during a certain time is important in ranch planning. Cordova et al. (1978) reviewed the literature of forage intake in early periods. Cook et al. (1962) analyzed the factors that might affect livestock forage requirements. Animal unit month (AUM) is the most widely used index to predict the forage requirement of livestock in USA. The AUM requirements vary with livestock type, age and gender. AUMs are used to define rangeland carrying capacity. Diet selection models were also developed to simulate selectively grazing (Blackburn and Kothmann, 1991; Hutchings and Gordon, 2001).

On a landscape scale, forage utilization differs within one pasture. The utilization heterogeneity might reduce rangeland carrying capacity. Harris and Asner (2003) found a grazing gradient on rangeland from remote sensing data. The mechanism of grazing distribution is not fully understood. Statistic methods are used to identify the major factors in affecting grazing distribution. The most important factors identified include slope, distance to water point or feed point and brush density in most studies (Bailey et al., 1996; Brock and Owensby, 2000).

Geographic information system (GIS) was used to study grazing distribution and proper carrying capacity. Geospatial analysis in GIS was used to derive the spatial pattern of grazing distribution (Namken and Stuth, 1997a; Brock and Owensby, 2000). The spatial pattern can be used to define proper carrying capacity through a GIS analysis (Namken and Stuth, 1997a; Guertin et al., 1998).

Utilization heterogeneity can be reduced through proper range management. Williams (1954) listed several practices to achieve uniform use of forage. Fencing and feed points are the major tools to control grazing distribution. Holechek (1988) proposed one method to adjust carrying capacity according the different factors.

Stocking rate is an important factor in range management. Gillen and Sims (2003) reported a negative relationship between cow weight per head and stocking rate. However, the relationship is limited to that special management scenario and the relationship of stock rate and ranch output may vary for different ranches. For a special operation environment, the relationship can be derived through experiments or mechanism based models. Tess and Kolstad (2000) described a cow-calf production model that includes details of livestock response to forage, genotype and management.

Plant and Livestock Interaction

Grazing is the most important plant-herbivore relationship in rangeland systems. Briske et al. (2003) summarized two major paradigms in plant and livestock relationships from an ecological view, equilibrium and state transition models. Equilibrium models are based on ecologically dynamic interaction of plants and animals. Noy-Meir (1975) proposed a predator-prey model to simulate grazing systems. Then a series of modifications were made to accommodate more sophisticated structures (Noy-Meir, 1978; Hu et al., 1997). State and transition models were introduced in 1990's. Current research of this field is still in conceptual development and the application of the model in range management is rare (Bestelmeyer et al., 2003; Stringham et al., 2003).

The results of grazing impacts on plant production from different studies are controversial. One viewpoint is that light grazing can enhance the forage production and heavy grazing may reduce the productivity (Hart, 1978; Lacey and Poollen, 1981; Hart, 1986). However, many research results suggested that grazing impact on production is small or uncertain (Heitschmidt et al., 1982b; Vesk and Westoby, 2001; Navarro et al., 2002; Gillen and Sims, 2003). Heitschmidt et al. (1982a) suggested that grazing may also reduce the nutrient content in forage.

The interactions between plant and livestock imply that carrying capacity is determined by livestock and plant. Several studies tried to define grazing capacity based on herbivore-plant dynamics (Wang and Hacker, 1997; de Mazancourt et al., 1998; de Mazancourt and Loreaua, 2000; Fynn and O'Connor, 2000).

Most rangeland plants have growing and dormant seasons. The phenology of the plants affects the nutrient and quantity of forage at different seasons. And the seasonal variations of plant may affect daily added weight of livestock (Rosiere et al., 1975; Ward, 1975).

Many rangeland models were developed for aid in grazing planning. Two example models include the grazing land Alternative Analysis Tool (GAAT User’s Guide, 1993) and Grazing Land Applications (GLA) (Stuth et al., 2002). These models require users to input available forage and livestock herd structure and the model can predict ranch outputs.

Hydrology and Erosion

Many hydrologic and erosion models are available for different temporal scales, spatial scales and complexity. These models can be divided into plot and watershed models according to the spatial scale and type of study areas. Plot models focus on small areas, the widely used plot models in USA are USLE/RUSLE. Watersheds models take a watershed as study area. Since a watershed consists of diverse slopes and channels, watershed models are generally more complex.

USLE is the first erosion model widely used in erosion prediction in USA. It is a lump-sum empirical model for plots with uniform slopes. RUSLE evolved from the USLE to allow temporal change of factors, such as erosivity (R), erodibility (K), and crop factor (C). Although USLE/RUSLE was mainly developed for cropland, a series of applications have been done on rangeland (Renard et al., 1974; Wischmeier and Smith, 1978; Simanton and Renard, 1992). Renard and Simanton (1990) described RUSLE and its application to rangeland erosion prediction. Many studies supported the use of USLE to rangeland erosion prediction (Renard et al. 1974; Johnson et al., 1980; Foster et al., 1981; Smith et al., 1984; Simanton and Renard, 1992). However, other studies opposed using USLE in rangeland erosion prediction. Trieste and Gifford (1980) applied USLE to rangeland on a per storm basis. The results showed that the model is not good for per-storm studies. Spaeth et al. (2003) compared erosions from rainfall simulators and prediction using RUSLE and USLE. They found that USLE tended to over-predict and

RUSLE tends to under-predict and the errors from RUSLE was lower than that from USLE.

With emphasis on watershed management of soil conservation and water quality, various watershed models have been developed. Singh and Woolhiser (2002) reviewed the major watershed hydrologic and erosion models. Watershed models are important in TMDL development. At present, most models are developed for agricultural lands and just a few models are for rangeland.

Watershed models are developed for different purposes. Consequently, watershed models can vary for temporal scale, spatial scale, watershed types and pollutant types. According to the temporal scale, watershed models can be divided into event-based or continuous-time types. The spatial scale may vary from small watersheds to large basins. The watershed land use types may be cropland, rangeland or mixed land use. The pollutant type may include sediment, nutrient, bacterial, fertilizer or pesticide.

There are several event-based models. ANSWERS (Area Non-point Source Watershed Environment Response Simulation) is an event-based watershed model for erosion and sediment yield control (Beasley et al., 1980). ANSWERS is primarily applied to a single storm and is a fully dynamic model. KINEROS (KINematic Runoff and EROSion model) is a physically-based model simulating the processes of interception, infiltration, surface runoff and erosion from small agricultural and urban watersheds (http://www.tucson.ars.ag.gov/kineros/).

Some watershed models are developed for pollutant prediction. AGNPS (AGricultural Non-Point Source) is a grid-based model developed by Agricultural Research Service (msa.ars.usda.gov/ms/oxford/nsl/AGNPS.html). AGNPS is an event-based model to predict soil erosion and nutrient transport/loadings from agricultural watersheds. AnnAGNPS, the later version of AGNPS, are used for annual simulation (Cronshey and Theurer, 1998). CREAMS (Runoff and Erosion from Agricultural Management Systems) is a field scale model for predicting runoff, erosion, and chemical transport from agricultural management systems (http://eco.wiz.uni-kassel.de/model_db /mdb/creams.html).

Some watershed models are intended for large watersheds. SWAT (Soil and Water Assessment Tool) is a distributed, continuous model to predict sediment and pollutant loads on large river basins (100 square miles) with different managements (http://www.brc.tamus.edu/swat/doc.html). SWAT was adapted from SWRRB, which is a distributed version of CREAMS. SWIM (Soil and Water Integrated Model) can simulate hydrology, erosion, vegetation growth and nutrient transport on large basins (100 - 20000 km^2) (http://dino.wiz.uni-kassel.de/model_db/mdb/swim.html). SWIM uses the GRASS interface and was adapted from SWAT and MATSALU. CONCEPTS (CONservational Channel Evolution and Pollutant Transport System) can simulate the evolution of incised streams and evaluate long-term impacts of rehabilitation measures to stabilize stream system and reduce sediment yield (http://msa.ars.usda.gov/ms/oxford/nsl/agnps/ Concepts/).

Most watershed models only have simple vegetation components. Many models assume that vegetation is constant during whole simulation period. With increasing requirements for vegetation management, watershed models begin to incorporate more sophisticated vegetation components. EPIC is a plot-based model developed by USDA-ARS to quantify crop loss from soil erosion (http://eco.wiz.uni-kassel.de/model_db /mdb/epic.html). WEPP (Water Erosion Prediction Project Model) is a process-based distributed continuous erosion simulation model with vegetation component (http://topsoil.nserl.purdue.edu/nserlweb/weppmain/wepp.html). SPUR (Simulation of Production and Utilization of Rangelands) has an elaborate plant component (http://eco.wiz.uni-kassel.de/model_db/mdb/spur.html). SPUR2000 was developed by integrating the climate and hydrology components of WEPP and the plant, livestock and economics components of SPUR 2.4 (http://www.nwrc.ars.usda.gov/models/spur2000/ index.htm). SPUR 2000 is a new generation model for rangeland systems. However, the applications of SPUR 2000 to rangeland watersheds have several difficulties, such as the huge parameterization data requirements and the challenging model validation which can be costly and time consuming.

GIS (geographic information systems) are used to enhance the applications of simulation models. GIS is particularly useful in distributed model parameterization and spatial result presentation. Sui and Maggio (1999) summarized the types of integration of GIS and hydrological models. Mankin et al. (2002) and He (2003) presented the integration of AGNPS in GIS interface. GRASS (Geographic Resources Analysis Support System) is a GIS interface in data management, image processing, graphics production, spatial modeling, and visualization for many simulation models. AGWA (Automated Geospatial Watershed Assessment) is an ESRI ArcView extension to provide GIS interface that can create input for KINEROS and SWAT from GIS coverage (Burns et al., 2004).

USLE/RUSLE was implemented on watershed scale in GIS environment. Several studies used GIS and USLE/RUSLE to estimate total erosion on watershed scale and erosion distribution (Mellerowicz et al., 1994; Cox and Madramootoo, 1998; Yitayew et al., 1999). In this type of application, a watershed is divided into many slope units, GIS is used to calculate the values of USLE factors from GIS layers or field data, and erosion rate in each grid is estimated by multiplying all USLE factors. Sediment yield of a watershed can be estimated from USLE erosion and sediment delivery ratios. Prediction from this method may be affected by resolutions of GIS layers (Molnaar and Julien, 1998).

Although many simulation models are available, the application of hydrologic and erosion models on rangeland is challenging. Weltz et al. (1998) reviewed the major models used in rangeland erosion and the major components in current models. Hydrologic and erosion models designed for rangeland watershed are still in development. Two issues make the rangeland application challenging. The first issue is the data requirement of model parameterization, validation and inputs. Many watersheds might not have sufficient data for these models. The second issue is that the results from models have high uncertainty, which implies that it is difficult to make a decision based on these results. Improvement of rangeland models is desired for better rangeland watershed management.

Interactions of Plants, Livestock and Erosion

Vegetation is a key factor in range management. Vegetation condition affects rangeland carrying capacity and erosion intensity. Generally speaking, high biomass can reduce erosion and sediment yield and perennial grass cover is more effective in reducing erosion intensity (Martin and Morton, 1993). Climate variations directly affect the vegetation condition and erosion, especially during drought periods (Emmerich and Heitschmidt, 2002).

Grazing could increase erosion intensity on rangeland watersheds. Livestock trampling reduces soil infiltration (Gifford and Hawkins, 1978). Livestock grazing also reduces above and below ground biomass (Trimble and Mendel, 1995; Mapfumo et al., 2002). Consequently, livestock grazing could increase runoff, peak flow of runoff, erosion intensity and sediment yield. The impacts can be severe under heavy grazing (Trimble and Mendel, 1995; Engels, 2001). However, the quantitative relationships are not fully understood and may vary region by region.

On the other hand, accelerated erosion may reduce rangeland productivity. For cropland, the EPIC model can predict the reduction of cropland productivity by erosion. However, no similar model is available for rangeland. Renard et al. (1985) showed that rangeland productivity decreased in southern Arizona in last century using historical data.

However, the impacts may vary site by site and there is no a quantitative relationship available to model the impacts.

Erosion models are becoming more sophisticated. New generation erosion models are usually based on a component structure. The major components of erosion models include climate, hydrology, plant, animal, soil and/or economics. Component-based models provide flexibility to incorporating different component models and the interactions among different components. However, parameterization of complex models requires lots of data inputs, which may be impractical for many rangeland watersheds. So selection of appropriate models need consider study objective, requirements, available data and budget.

2.2. Economics in Range and Watershed Management

Economics is important in both range and watershed managements. The selection of proper economic methods may depend on study purposes and available data. This section focuses on three topics. The first topic is the major economic techniques in natural resources management. The second topic is the economic models in watershed management. The third is the economics in range management.

2.2.1. **Summary of Economic Methods**

Various economic techniques were used in natural resources management. The methods in assessing the economic efficiency can be grouped into four categories:

budgeting, cost benefit analysis (CBA), single objective optimization and multiple criteria decision making (Conner, 1993; Wang, 1993). The following subsections review these techniques one by one.

2.2.1.1. Budgeting

Caton (1957) defined budgeting as "a device, a means of recording and giving logical unity and structure to the organization and operation of a ranch or farm" and proposed a theoretical framework and procedure of budgeting in range improvement. Numerous studies used budgeting in range management. Holechek (1996) used the average budget of a typical medium size ranch to analyze the financial return under different range conditions. Teegerstrom and Tronstad (2000) developed a budget analysis tool for ranchers in Arizona based on the historical data. Pimentel et al. (1995) analyzed the cost of erosion and possible benefit from conservation using rough estimated value. Gassman et al. (2003) derived the budgets of 15 options of pollution reductions. Compared with other methods, budgeting is simple and easily understood.

However, budgeting analysis has several disadvantages. Firstly, budgeting does not evaluate economic efficiency based on rigorous economic theory. Secondly, non-market benefits and costs are not included in budgeting. Thirdly, a ranch usually has a lot of options and optimization methods are more efficient in finding the best option (Child, 1975). In a word, budgeting is not a solid economic method to assess the economic efficiency of a project. Many studies may require more complicated methods.

2.2.1.2. Cost Benefit Analysis

Cost benefit analysis (CBA) is a standard method of economic analysis for public or private projects. It is mandatory on all U.S. government projects costing $100 million by Executive Order 12291 issued by President Reagan in 1981. CBA is based on solid economic theory, such as the opportunity (shadow) cost and the value of time. Thus it is a useful tool to compare the economic efficiency of different alternatives.

CBA can be classified as two types according to their implementation time. Retrospective CBA, or descriptive CBA, is used to assess implemented projects. The retrospective CBA is made after a project is implemented. Consequently, the impacts could be measured through historic data, and then economic efficiency is assessed from measured results. Results from retrospective CBA are usually reliable if the projects have good controls. McLaughlin (1993) compared the income difference between two villages with and without soil conservation. The method can be used to test previous CBA. However, this method is rarely used in application. The other type of CBA is mainly used to analyze a project in planning stage. Lots of literature about CBA applications in rangeland improvement is available (Lloyd, 1959; Caton et al., 1960; Cotner, 1963). McCorkle and Caton (1962) proposed the guidelines to assess range improvement using CBA. Clark (1996) reviewed the major CBA methods used in assessing environment degradation.

In some circumstances, if environmental objectives in physical units are known, then cost effectiveness analysis (CEA) is an alternative to CBA. Unlike CBA, CEA does not require to estimate benefits from environmental improvement that may be difficult in some applications. In this sense, CEA is simpler than CBA. Thus CEA was used in many environmental applications (Johnson et al., 1980; Srivastava et al., 2002; Khanna et al., 2003).

However, traditional CBA may not be suitable in certain circumstances. For the problems with continuous variables or huge number of alternatives, it is infeasible to list the costs and benefits for each option and to compare them. Optimization techniques may be more suitable for this type of problems. Furthermore, CBA cannot deal with the decision problems with multiple criteria. Multiple-criteria decision making techniques may be more suitable for this type of problems.

2.2.1.3. Single Objective Optimization

If a decision problem has continuous decision variables or huge combinations of options, the problem can be formalized as an optimization problem. Then various optimization techniques can be used to solve this type of problems. Single objective optimization techniques are basic tools in economic analysis such as production, consumption and natural resource allocation (Mas-Colell et al., 1995). Multi-objective problems are usually converted into one or many single objective optimization problems.

The techniques in economic optimization include marginal analysis, linear programming, nonlinear programming, optimal control, and pseudo optimization techniques.

Marginal Analysis

Marginal analysis is a basic tool in microeconomic analysis. Several studies used marginal analysis to find the optimum options in range improvements. Radar (1963) used marginal analysis to determine the best level of input of range improvements. Cotner (1963) used marginal analysis to determine the optimum timing of range improvements. Dickerman and Martin (1967) proposed a theoretical model to determine the best investment (time and magnitude) of range forage improvement using marginal analysis. Ciriacy-Wantrup and Schultz (1957) emphasized marginal analysis and linear programming can be used for long-term objective. Pearson (1973) used marginal value of grazing to derive maximum profit.

Marginal analysis in range management may be theoretically sound. However, all these studies assume that management response relationships were known, which is not true for many range management problems. In fact, available management-response relationships are highly uncertain, thus marginal analysis may not be practical for most range improvement analysis (Brown 1967).

Liner Programming (LP)

Since the invention of the Simplex Algorithm in 1947 (Dantzig, 1951), LP has been used in various management problems including range management. Even a large LP problem can be solved easily using widely available commercial software. The applications of LP to range management are extensive. Some early examples include Neilsen et al. (1966) and D'Aquino (1974). McCorkle (1957) introduced a framework of LP in range improvement. Child (1975) used LP to determine the best ranch management with limited resources. Evans and Workman (1994) used LP to optimize range improvements, such as revegetation, prescribed burning and chemical brush control. If adding a temporal index, LP can also be used in multi-period optimization problems on range management (Bartlett et al., 1974). Bernardo et al. (1992) maximized the net income of multiple uses of range resources. Namken and Stuth (1997b) used LP model to select the best sites for brush treatment. In this type of application, the objective of LP problems is either to maximize net returns or to minimize associated costs.

Nonlinear Programming (NLP)

For problems with nonlinear relationships, non-linear programming provides an alternative for more accurate presentation of application problems. Although there are some commercial software programs that can solve NLP, such as GAMS with the appropriate solvers, there are restrictions on problem types and variable numbers. Because of the algorithm restriction, NLP has rarely been used in range applications.

Furthermore, the solutions from NLP algorithm are locally optimal, and the results may need further testing to find a global optimum.

Combinational Problem

Many cropland erosion control projects were formulated as combination problems (Srivastava et al., 2002; Khanna et al., 2003; Veith et al., 2003). In a typical model, the study area is divided many plots and each plot has several conservation options, then the objective is to find the best combination of options for each plots with minimal implement costs or maximal net returns. However, this structure is not suitable in rangeland, and few studies applied combination problems in range management.

Dynamic Programming and Optimal Control

Dynamic programming and optimal control have been used to study the risk of climate and market variation (Rodriguez and Roath, 1987; Carande et al., 1995). Hu et al. (1997) used dynamic programming to optimize the grazing strategy with wind erosion control in a livestock production model in rangelands. Cash (2000) used optimal control techniques to study optimal stocking rate based on economic criteria.

However, current models on range dynamics were based on very simple assumptions about ecosystem structures. For example, most studies assume uniform biomass production and utilization, which is not true for most grazing lands. The results from these studies were not sophisticated enough for application on a management level.

Furthermore, it is challenging to consider both spatial heterogeneity and temporal randomness simultaneously in one model.

2.2.1.4. Multiple Criteria Decision Making

Multiple uses of range resources on public lands can be formulated as multiple criteria decision making (MCDM) problems. A brief introduction to MCDM can be found in Ramesh and Zionts (1996). Eskandari (1997) summarized the major methods in solving multiple criterion decision making (MCDM). Multi-objective programming is similar to MCDM (Steuer, 1996).

The methods to solve MCDM can be divided into two major types, vector optimization methods and utility methods (Ramesh and Zionts, 1996). The vector method tries to find all the sets of efficient solutions for a problem, and ranking or selecting a practical solution from efficient solution set is left to decision makers (DMs). The method does not require DMs to interact during searching solutions. There are several problems with this method. First, the size of efficient sets increases very quickly with increasing the number of objectives, which make it difficult to list, compare and compute the complete efficient sets for a large problem. Second, selection from efficient solution sets could be a challenging job. Utilization methods are ranked different the efficient solutions according to utility functions. Utility functions define the preference order of DMs. The function can be used to select the best solution from the non-dominated sets. Different utility functions will create different solutions.

MCDM problems are usually converted into one or a series of single optimization problems. A decomposed problem can be solved through single-objective optimization techniques. For environmental and natural resources management problems, environmental control objectives are generally converted to constraints and an economic objective is optimized with environmental constraints (Tecle, 1988; Prato et al., 1996; Srivastava et al., 2002; Veith et al., 2003).

Although various economic methods are available, the selection of a method for special application needs to consider study objective and data availability. In natural resource management, these methods are incorporated into models to assess economic impacts. The following two sections review the major methods in watershed management and range management.

2.2.2. **Economic Models in Watershed Management**

Watershed management is an approach for solving water-related problems. TMDLs are examples of using watershed management to improve water quality. Economic analysis of TMDL program may have different focuses, such as minimizing the total cost of a TMDL, allocating the cost burden on different polluters, comparing the efficiency of different policy instruments. Results from economic analysis can be used in selecting best alternatives, making cost-benefit analysis (CBA), or designing policy packages.

Various economic methods were used in watershed management. Easter (1988) discussed economics of watershed management using CBA. Kim (1984) used CBA to analyze grazing impacts on a rangeland watershed. The economic component in SPUR can simulate budgeting for range operation. Several studies used the optimization techniques in watershed pollution control (Johnson et al., 1989; Prato et al, 1996; Srivastava et al., 2002; Khanna et al., 2003; Veith et al, 2003). All these studies considered whole watersheds as representative farmers and the objective is to find the solution with the least cost while meeting environmental control objectives. Sun et al. (1996) discussed stochastic dominance in a case study of selection of BMPs under climate and market uncertainty.

To develop optimization models, researchers need to determine management-response relationships for their special areas. Management-response relationships of rangeland are usually complex, and current knowledge of the relationships are limited and with high uncertainty. Simulation models are the major tool to derive these relationships. However, current simulation models are mainly developed for cropland watersheds, and most literature on optimization of watershed management has concentrated on cropland watersheds.

It is difficult to solve optimization problems with huge numbers of options and complex embedded sub-models. Two approximation methods are used in simplifying this type of problem. The first method is to find the approximate solution instead of the optimum solution. For combination problems, approximation techniques, such as genetic algorithms (GA) and simulated annealing (SA) are used to find a near optimum with fewer restrictions of function properties. Srivastava et al. (2002) developed a model to select the BMPs that minimize the pollutant load with a cost constraint or maximize the net return with a pollutant load constraint. They integrated GA and AnnAGNPS in one optimization model. Veith et al. (2003) studied the best BMPs for a watershed with the least cost while meeting the sediment control objectives. USLE and a sediment delivery ratio were used to simulate the sediment yield of the watershed. The method has several advantages. The algorithm is robust to different model structures, the results have multiple feasible solutions and the solutions can theoretically reach an optimum. However, the time for solving such problems may be very long and the method requires a validated simulation model. Khanna et al. (2003) converted an integer programming into a linear programming for near optimum solutions by using a simplified land plot structure.

The second approximation method is to simplify the relationships of the management-response relationship. Then optimization is made over these simplified relationships, and the solution for a new problem is considered as an ‘optimum’ solution for the original problem. Several studies used linear programming to solve the optimization problem. Beaulieu et al (1998 and 2000) used a spatial linear programming model in policy impact assessments. Heilman et al. (2003) used linear programming to calculate the abatement cost curve for sediment control on rangeland.

The simplified relationships may be derived from simulation models or statistic relationship of observation data. Khanna et al. (2003) used a simulation model to decide the hydrological relationship of management and sediment yield. The original integer programming was converted as a LP problem. Ancev et al. (2003) used LP to maximize benefits from controlling phosphors using BMPs in a watershed. Many applications also used this approximation (Johnson et al., 1989; Eskandari, 1997; Namken and Stuth, 1997b; Yakowitz et al., 1992; Zaidi et al., 2003).

Few studies have been made to derive optimal spatial pattern of BMPs on rangeland watersheds. There are some difficulties in formulating rangeland BMPs as an optimization problem. The first difficulty is spatial segmentation of rangeland. For farmland watersheds, land use parcels are used as spatial units. However, for grazing land, such configurations do not exist. Even in a pasture, vegetation growth and livestock grazing may vary significantly. Furthermore, pasture arrangements are not fixed, and pasture patterns can be changed under different management practices. High spatial heterogeneity on rangeland makes rangeland modeling more complex, which may be one of the major reasons that few studies on this topic have been done so far.

The second difficulty is that the input-output relationships of a ranch could be very complex. Forage production on rangeland highly depends on climate and may vary year by year or season by season. At the same time, ranching outputs depend on both forage production and livestock management. Furthermore, range management needs to consider the inter-year impact because of the transition of vegetation and livestock herd between consecutive years.

The third difficulty is that current knowledge on rangeland is limited. Lots of research has been done on croplands. Many models were developed and validated on cropland. However, the research for rangeland is much less mature, and few models have been developed for rangeland.

Developing an economic optimization model for rangeland watershed may enhance TMDL on rangeland watersheds. Lovejoy et al. (1997) discussed that economic optimization is necessary in watershed management. A well designed model and friendly interface processes are particularly useful to improve rangeland environment.

2.2.3. Economics in Range Management

Range management has expanded its scope gradually since it emerged in the early twentieth century. To deal with rangeland degradation caused by uncontrolled grazing in western USA in the nineteenth century, range management emerged as a new field to study proper approaches to recover and maintain rangeland functions. At the beginning, range management focused on grazing controls, such as fencing and water points, to protect rangeland. In the middle of the twentieth century, range improvements, such as seeding and brush control became the new focus in range management. In late twentieth century, rangeland management made more efforts on maintaining rangeland ecological function, environmental function, watershed function and sustainable use.

Ranching is a distinct industry that deals with plants and livestock in one system, which is different from other agriculture productions system (McCorkle, 1957; Holechek et al., 2001). According to Holechek et al. (2001), modern range management is defined as:

> the manipulation of rangeland components to obtain the optimum combination of goods and services for a society on a sustained basis.… Range management has two basic components: (1) protection and enhancement of the soil and vegetation complex, and (2) maintaining or improving the output of consumable range products, such as red meat, fiber, wood, water, and wildlife.

With increasing range improvement projects, range specialists needed to assess economic efficiency. Economic methods were used for this type of study. Range economics emerged as a new field for this special purpose. According to Workman (1986), range economics is defined as:

> the science of applying the principles of economics and range management simultaneously to determine the economic consequences of decisions involving the use, development and/or protection of rangeland.

Much research on the economics of range improvement has been published (Caton et al, 1960; Radar, 1963; Roberts, 1963; Wang, 1993; Evans and Workman, 1994; Ethridge et al, 1997). The Western Agricultural Economics Research Council Committee on Economics of Range Use and Development made a series of publications on this field to prompt applications of range economics (Baker and Plath, 1957; McCorkle, 1959;

Roberts, 1962; Roberts, 1963; Roberts, 1964; Wennergren, 1965; Wennergren, 1966; Neilsen, 1967). Dawson et al. (1983) assessed the economic effectiveness of BMP in controlling non-point pollution on rangelands.

The concept of multiple uses of public lands was recognized at the middle of the twentieth century (McCorkle, 1959; Fulcher, 1967). The Multiple-Use Sustained-Yield Act (1960) mandated that management of public lands owned by USFS must be based on multiple use concepts. Multiple uses of rangeland can be formulated as a multi-objective problem. However, some objectives are not quantitatively measurable, for example, biodiversity and recreation value. Some values of natural resources lack market values, thus the measurements of these values need indirect valuation techniques, such as revealed preference, stated preference, etc, which are generally too costly for extensive land use like rangeland. The conflicts among different uses require careful planning of range resources to meet the different objectives set by multiple use requirements.

Overgrazing on rangeland caused accelerated erosion (Gifford and Hawkins, 1978; Blackburn, 1983; Jacobs, 1991; Trimble and Mendel, 1995). Impacts by onsite erosion were verified by many studies and improvement practices were used to reduce the impacts (Gifford and Whitehead, 1982; Renard et al., 1985; Evans and Workman, 1994). However, off-site effects, or the externalities associated with erosion, were rarely included in decision making of range management. Neglect of off-site impacts may cause less range conservation than the optimum level from a social perspective.

Environmental economics can be useful in valuing environmental service of rangeland and erosion externality. Environmental valuation techniques provide a way to monetize the rangeland services that do not have market prices, such as recreation demand of open space (Brown, 1964; Wennergren, 1964; Stevens and Bollman, 1966). Valuation results are useful in deciding proper managements for multiple uses of range resources. In addition, externality theory justifies government intervention of proper level of resource allocation to different uses to maximize social benefit through effective policy instruments.

2.3. DSS in Natural Resource Management

Scientific research has accumulated a lot of knowledge, in the forms of data, theory and models for resource management. The knowledge is critical in improving natural resource managements. Transferring the knowledge to decision makers could be difficult for the requirements of cost and human resources. DSS is particularly useful in transferring the knowledge to users. DSS is a platform that provides easy access of complicated models and data that may be otherwise difficult for inexperienced users to use. A typical DSS includes three basic components: database, model bank, and user interfaces (Loucks, 1995; Shim et al., 2002). However, the structure and functionalities of DSS may vary in different applications. Some DSS may include only one complicated model and interface for user inputs and outputs, such as SPUR (Carlson et al., 1993). Other DSS may provide more flexibility for users to solve different types of problems.

With the development of information technology, DSS is experiencing rapid changes. Optimization-based DSS and web-based DSS are the innovative and active fields in the new millennium (Shim et al., 2002). Optimization-based DSS includes formulation, solution and analysis for complex problems to aid users in decision making. Web-based DSS provide the widest access of a DSS. This section reviews the literature of several subfields of DSS application on natural resource management.

2.3.1. **DSS in Range Management**

DSSs have been developed to aid range management. Stuth and Lyons (1993) discussed the major parts of DSS in range management. Sugumaran (2002) described a DSS framework for range management in India. GLA is a range management DSS for assessing the economic and environmental impacts of various grazing land managements (Stuth et al., 1990 and 2002). GLA includes climate, soil, plant, livestock and economic components. The models in GLA included an expert system, dynamic programming, integer programming, linear programming, mixed integer programming and multi-objective programming. The model provided users the information of forage capacity, optimum livestock-wildlife mix, grazing schedules, investment analysis and energy balance. Mohtar et al. (2000) described a web-based grazing simulation models that can simulate plant growth, livestock grazing and associated nitrogen loss of study areas. However, the model requires lots of inputs that may not available for many ranches.

2.3.2. DSS in Watershed Management

DSSs have been developed for watershed planning and management. Prato et al. (1996) described a DSS model for agricultural watershed. Beaulieu et al (1998 and 2000) linked LP and GIS for watershed erosion control. Bathurst et al. (2003) developed a DSS for agricultural economics to maximize income for agricultural basin. He (2003) developed a DSS that integrated ArcView GIS and AGNPS for soil erosion analysis on watershed. Engel et al. (2003) introduced L-THIA to assess hydrological impacts of land use for watershed in a web-based environment. The DSS used GIS to delineate watersheds from embedded DEM and then the L-THIA model was activated to evaluate erosion impact from land use change.

2.3.3. Spatial Decision Support System

Spatial decision support systems (SDSS) expand traditional DSS by incorporating geospatial functionality into DSS. A SDSS typically includes modules of database, models, knowledge base and interfaces. A database module in SDSS includes stored spatial and non-spatial data. Geospatial models are the unique component of SDSS that support geospatial analysis. GIS is the major spatial tool to manage spatial data and make geospatial analysis. SDSS provides users the functionality to edit and manage spatial features. Lovejoy et al. (1997) discussed the integration of GIS and hydrologic models into SDSS for water quality management. Since spatial heterogeneity is a major characteristic of range management, SDSS provides a system platform to present and analyze spatial factors, such as soil, precipitation, forage production, grazing, hydrology and erosion.

SDSS have mainly been developed for natural resource management. Matthews et al. (1999) described a SDSS for land use planning. The SDSS used GIS and genetic algorithms in knowledge based system to optimize land use patterns. Economic optimization over space was considered as an essential part of SDSS (Lovejoy et al., 1997). Prato et al. (1996) described a SDSS with economic, environmental and ecological modules, which allowed users to compare the management plans. Beaulieu et al (1998 and 2000) developed SDSS that used GIS to visualize results from LP. Riedl et al. (2000) developed a graphic interface that allows users to analyze silvicultural management through flowcharts.

2.3.4. **Web-based DSS**

The internet provides the most efficient way to distribute information. Compared with PC-based DSS, web-based DSS has several advantages. First, update of web-based systems and information is much faster. This is particularly important for some applications that are based on real-time information, such as severe weather forecast. For example, Jensen et al. (2000) developed a web-based system that provided the just-in-time weather data and simulation models for crop management in Denmark. Second, web-based DSS usually provides the widest access to many users simultaneously. Third, most web-based DSS only need a browser to access a DSS, which is important for many nonprofessional users. Finally, most web-based applications have friendly interfaces for nonprofessional users.

Web-based DSS were used in various resources management. Zhu and Dale (2001) described a web service providing analytic hierarchy process (AHP) for environment management problems. Ludwig et al. (2003) presented a web-based DSS to study global change of small catchments. The web-based system developed by Engel et al. (2003) used a web map to allow users to select interested watersheds and to input non-spatial through forms. Markstrom et al. (2002) discussed the techniques of using the web to distribute spatial data and hydrological models. Mohtar et al. (2000) present a web-based grazing model. The system used forms to input data and the output could be viewed as tables or figures, which are easily understood for nonprofessional users. Pandey et al. (2000) developed a web-based tool to assess the long-term hydrological impacts logical of land use change.

Web-based DSS are still in development. Several issues are critical for a successful DSS. The first issue is to clearly define the problem that a DSS is intended to solve. The second issue is the inter-operability of DSS. Because of openness of web-based application, the interaction between different systems is a basic requirement, which implies that input and output standards must be clearly defined.

2.4. Summary

Rangeland BMPs are critical to implement TMDL and to maintain rangeland sustainability. The deficiency of assessment tools makes TMDL planning on rangeland watershed more difficult. Current literature has accumulated data and knowledge that are useful to improve such type of decisions. The integration of current knowledge into DSS can promote the knowledge transfer for a better decision.

Range science and range economics provide analytical tools to integrate the knowledge for assessing the impacts of range BMPs. Although current understanding of rangeland system is still limited, a model with good design will provide useful information for a better decision. SDSS support analysis of spatial features that are particularly useful in natural resources management. Web-based DSS provides more efficient tool to distribute advanced analysis techniques to non-expert decision makers. Web-based applications provide the widest access of information in an economic and fast way. Previous applications demonstrated the potential of such systems. Web technique development will provide more flexibility and power of SDSS functionality, including customized pages, long transaction service, and spatial data services.

CHAPTER 3 WATERSHED ECONOMIC MODEL DEVELOPMENT

Rangeland systems are complex and current knowledge of range processes is limited (Klemmedson et al., 1978; Holechek et al., 2001). Biophysical simulation models are major research tools to predict management impacts (Carlson et al., 1993). Biophysical models can be applied in three ways: 'use an existing model, modify an existing model, or build a model for designed to meet the specific needs' according to Larson et al. (1982).

Although various watershed models have been developed, no existing watershed models meet the objectives of this study. This study needs to assess the impacts of different BMPs on sediment yield and ranch profitability. Most watershed models do not have economic components, thus cannot predict the economic impacts. Furthermore, because most BMP structures can function for decades, long-term cost-benefit analysis of BMP practices is needed. As described in Section 2.1, event-based models, such as KINEROS2, are suitable for simulating short-term hydrological and erosion impacts. Many long-term watershed models use very simple vegetation components based on simple assumptions. The inability to predict long-term impacts of management on plant and livestock output excluded direct incorporate these models in this study.

SPUR 2000 is a comprehensive rangeland simulation model that has the major components, including an economic component, of rangeland system. Three reasons preclude adopting SPUR model in this study. First, parameterization of SPUR is difficult and validation of SPUR was only done in small area of northwestern USA. There are no validated SPUR parameter sets for southwestern USA. Second, SPUR does not explicitly define BMP managements. Third, SPUR may not a suitable model in web-based application for the execution time and model complexity. SPUR uses daily-based simulation, the input requirements and execution time may be too burdensome for a web-based application.

This dissertation developed a new model to meet the study requirements. This chapter describes the details of the watershed model development. This chapter includes 11 sections. Section 3.1 defines the model requirements. Section 3.2 introduces the study scope. Section 3.3 presents the theoretical model. Section 3.4 defines the model configurations. Section 3.5 and 3.6 describe the equations for the static and dynamic models respectively. Section 3.7 describes the code to solve the models. Section 3.8 describes the model parameterization. Section 3.9 introduces possible model extensions. The final section summarizes this chapter.

3.1. Objectives and Requirements of the Model

The objective of model development is to provide an analysis model to assess the economic impacts of different management practices in abating sediment yield on rangeland watersheds. The models are the major analytical framework in the SDSS through which users can formulate and solve their problem by specifying their model inputs. The inputs that users can control include spatial and non-spatial management, policy settings, and economic parameters.

To meet this objective, a series of requirements were defined in model development. The requirements help to clearly define the model structures and functionality. For the inputs, the model should include the major factors affecting the watershed hydrology and ranch production. These factors are divided into exterior factors and interior factors. The interior factors can be controlled in a watershed, such as the management and policy settings. The exterior factors, such as climate and prices, are out of control on the watershed level. Outputs should include ranch and sediment outputs. Furthermore, to extend this system to other watersheds, the data to parameterize the model should be available for most rangeland watersheds.

The model should adopt a component-based structure. A component-based structure is widely used in biophysical watershed models (Carlson et al., 1993). The component-based structure is compatible with many watershed models. In addition, the component-based structure provides the convenience to upgrade a component or to contain different functions for one component in one model.

The model should incorporate both spatial and temporal dimensions. The model should consider the distributed nature of watersheds to represent the spatial heterogeneity with reasonable resolution. The resolution selected should represent the major spatial heterogeneity of plant, grazing and erosion processes while keeping problems tractable.

The model should include static and dynamic types for different analysis objectives. The static model is intended to predict long-term annual average relationships. The dynamic model is intended to predict dynamic changes during a study period.

The time to execute a typical analysis should be limited for a web-based application. The web-based application requires that the response time should not be more than several minutes. Although users of this type of application can tolerate a longer response time, a quick response time is preferred. It is critical to define a reasonable level of model complexity and to select efficient algorithms to meet the requirement of response time.

The models are designed for managing watersheds dominated by grazing lands. Generally, a watershed is mixed with different land uses. Since this study focuses on the impacts of rangeland BMPs, only erosion from grazing land is considered, although urban and construction areas may be important sources of sediment in some cases. Furthermore, the erosion types considered in this study include upland erosion and sediment transportation. Gully or channel erosion is not considered in the model.

This study focuses on grazing lands in southwestern USA. Since the knowledge of range systems is limited, empirical relationships developed from the data in southeastern Arizona were used if the mechanism-based relationships were not available. These empirical relationships may not be suitable for other areas with different climate and geographic characteristics. Users may need to check these relationships before applying the model to other regions.

This study uses a representative ranch of a watershed as the planning focus. The cost and profit is defined on watershed level. The results from the models do not evaluate the economic impact distribution of a conservation plan among different ranchers within a watershed.

3.2. The Theoretical Model

The key point in range management is proper allocation of biomass resources for different biomass uses. Forage biomass can be grazed for profit, or left ungrazed to protect soil and maintain range condition. Trade-offs among different biomass uses is a complex issue for the decision needs to consider both natural and social factors. Biophysical models can be used to understand the relationships systematically through optimization techniques. In this section, a general range management problem is formulated, and a practical model is derived from the general problem through a series of simplifications. The practical model is used as the framework of model implementation.

Ranching on grazing lands is a production system. A ranch is a production unit that has individual management strategy and financial accounts. Watershed boundaries usually do not match ranch boundaries. Since the objective of this study requires considering economic impacts in a watershed, the models treat all pastures within a watershed as one ranch. Similar methods are widely used in watershed analysis (Srivastava et al., 2002; Ancev et al., 2003; Khanna et al., 2003; Veith et al., 2003). The method provides a simple way to assess the total cost and benefit of environmental plans for a watershed. However, the results from this type study need further analysis if the impact distribution among different ranchers is concerned.

Ranch production can be described by a production function. In a ranch, the inputs include cows, bulls, land, forage, feedstuff, infrastructure, labors, machinery, etc. The outputs are cull cows, cull bulls, sold calves and yearlings, etc. The inputs and outputs can be recorded in either physical or monetary units. The production function of a ranch is assumed to be:

$$Y = F(X, E) \qquad 3\text{–}1$$

where X is the vector of all marketable inputs in physical units, E is the vector of natural resource inputs, Y is the vector of ranch outputs in physical unit, and F(.) is the best available technology that converts inputs to outputs.

If there is a value system for all inputs and outputs, then the profit function can be calculated as:

$$\begin{aligned} PRO &= P_Y * Y - P_X * X - P_E * E \\ &= P_Y * F(X, E) - P_X * X - P_E * E \\ &= G\,(P_Y, P_X, P_E, X, E) \qquad 3\text{–}2 \end{aligned}$$

where PRO is the net profit of ranch production, G(.) is the production function in monetary units, P_Y is the vector of output prices, P_X is the vector of input prices, P_E is the vector of social value of natural resources.

Profit maximization is assumed as the objective of ranch production. However, the objective needs some qualification. Ranch production needs natural resources as indispensable inputs, whose values are not, or only partially, counted in ranch production cost. For example, grazing fees on public lands could be lower than their market value, and environmental degradation from grazing is not explicitly counted as ranching cost. Since most grazing lands in western USA are public lands that are required to support multiple uses, the ranch production objective in this study incorporates these factors.

Generally, ranch production can be formulated as a MCDM (Multiple Criteria Decision Making) problem.

$$\text{Object: } OBJ_i \qquad i = 1, \ldots, I$$
$$\text{St: } Y = F(X, E) \qquad 3\text{–}3$$

where OBJ_i is a series of objectives, i is the index of objectives, and St is the abbreviation for "subject to" the constraints, X, E and F(.) are the same as Equation 3-1. The objectives may include maximizing income, minimizing sediment yield, and/or maintaining rangeland condition. For rangeland, three objectives are of particular concern: ranch profit, rangeland condition and water quality. These objectives have different priorities in management.

The MCDM problem can be converted to a single objective optimization model. The conversion set the objectives with higher priority as the constraints and the objective with the lowest priority as the single objective. For public grazing land, rangeland sustainability and multiple uses have higher priority. Proper utilization is critical in maintaining rangeland productivity. Proper utilization should keep sufficient forage for ecological functions, such as maintaining the productivity of major species, and providing sufficient forage for wildlife. If a threshold value exists, the rangeland condition objective and multiple-use objective can be converted into a utilization constraint. Although a forage utilization constraint may help to reduce soil erosion, the constraint may not provide sufficient soil protection of watersheds. Assuming that sediment yield is the major environmental concern of watersheds, the model explicitly adds a sediment yield constraint to ensure meeting sediment control objective.

Then the CDMA problem is converted to the single objective problem to maximize ranch profit with several constraints. The constraints include resource and production capacity constraint as well as a grazing constraint and sediment constraint.

$$\begin{aligned} \text{Max} \quad & PRO \\ \text{St.} \quad & Y = F(X, E) \\ & U <= U^{*} \\ & SY < SYO \end{aligned} \qquad 3\text{–}4$$

where U is the utilization variable, and U^* is the threshold value of utilization, SY is the sediment yield variable, and SYO is the objective of sediment yield control, and other symbols have same meaning as in Equation 3-3. The natural resource inputs of ranch production, E, is a function of U and SY, i.e. E = E (U, SY). The new maximization problem is the general representative of the economic models in this study.

Ranch production requires different types of inputs. The inputs can be divided into variable inputs and fixed inputs. The amount of variable inputs is adjusted with production scale. The amount of fixed inputs is not adjusted with production scale in the short-term. The fixed inputs are mainly the infrastructure, including buildings, fences, water points, etc. To maximize their profits, ranchers must select the best input management strategy by adjusting the variable inputs in the short-term and fixed inputs in the long-term. The inputs can also be divided into non-spatially related and spatially related inputs. The non-spatially related inputs affect the production only by their amount, while the spatially related inputs can affect the production not only by their amount but also their location. By reclassifying the inputs, Equation 3-4 is converted to Equation 3-5,

$$\begin{aligned} &\underset{(X_{VS},\, X_{VNS},\, X_{FS}\; X_{FNS})}{\text{Max}}\ PRO \\ &\text{St.}\quad Y = F(X_{VS}, X_{VNS}, X_{FS}, X_{FNS}, E_S, E_{NS}) \\ &\qquad\; U_S <= U_S^* \\ &\qquad\; SY <= SYO \end{aligned} \tag{3–5}$$

where X_{VS} is the vector of spatial variable inputs, X_{VNS} is the vector of non-spatial variable inputs, X_{FS} is the vector of spatial fixed inputs, X_{FNS} is non-spatial fixed inputs,

E_S is the vector of spatial natural resource inputs, and E_{NS} is non-spatial natural resource inputs.

By adding the spatial index to the spatial variables, the model is converted to a spatial optimization problem. Generally, spatial optimization is difficult to solve. Furthermore, for most rangeland watersheds, the knowledge of production functions is incomplete and most rangeland does not have enough information to parameterize spatial inputs with high resolution, so further simplification is made to approximate the relationships.

Discretization of spatial and temporal space is used to approximate the continuous surface. A study area is segmented into small spatial patches with homogeneous attributes, which is widely used in hydrological and erosion modeling. For a given set of spatial infrastructures, the spatial configuration is determined, then Equation 3-5 is simplified by setting the spatial fixed input variables as constant. The optimization problem for a given infrastructure setting is:

$$\max_{(X_{VS},\, X_{VNS})} PRO$$

$$\begin{aligned} \text{St.} \quad & Y = F(X_{VS}, X_{VNS}, X_{FS}, X_{FNS}, E_S, E_{NS}) \\ & U_S <= U_S^* \\ & SY <= SYO \\ & X_{FS} \text{ are given} \end{aligned} \qquad 3\text{–}6$$

Equation 3-6 is the theoretical model in this study. The solution is for short-term management because fixed inputs are set to be constant. In other words, for a set of spatial management and sediment control objectives, the solution from the model gives the ‘best ’grazing management to maximize the profits and to meet all the constraints given the current infrastructure.

For a given set of infrastructure, the number of solutions for each SYO in Equation 3-6 can be zero to many. In the domain of all feasible solutions, there is a mapping between PRO^* and SYO. The mapping can be represented as a function:

$$PRO^* = H(SYO) \qquad 3\text{–}7$$

The curve could be an inverted ‘U’ shape (Figure 3-1). However, only the left part of the curve is reasonable, as the points in the right part are dominated solutions. If a problem does not have any sediment control objectives, the optimum ranch profit is PRO_0^* with sediment yield SY_0 (Figure 3-1). However, if the sediment yield constraint is binding, the optimum profit is reduced to meet the sediment requirement.

Since the production function, F(), in equation 3-1 is assumed to be the best technology for the ranch production, the curve from equation 3-7 is the short-term production frontier of a representative ranch for a given price system and infrastructure. In the short-term, infrastructure is considered constant, thus ranchers can only adjust variable inputs.

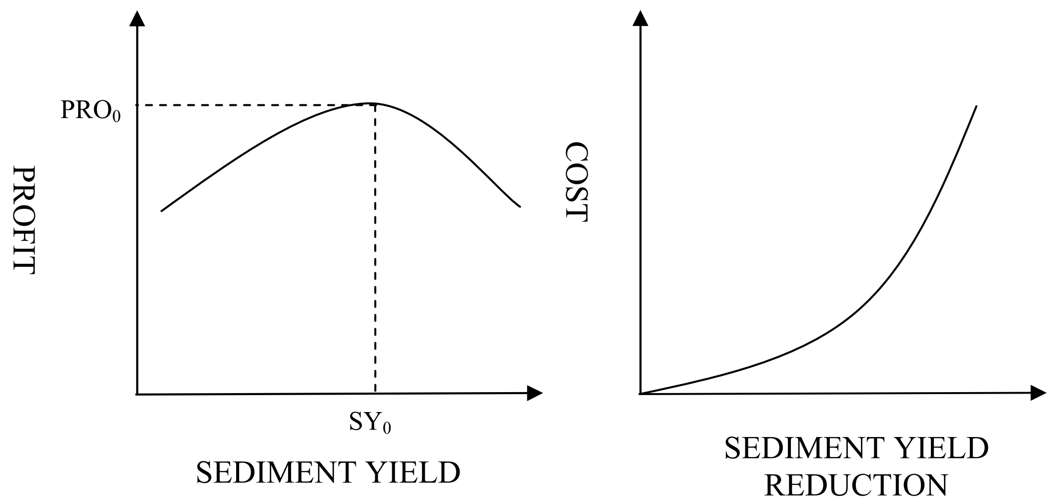


Figure 3-1 Illustration of production frontier (left) and abatement cost curve (right)

In the long-term, ranchers can adjust both variable and fixed inputs, and the corresponding curve is the long-term production frontier. The long-term production frontier is the envelope of a series of short-term production frontiers, thus the curve could be derived from a series of short-term production frontiers under different infrastructures. For each given infrastructure, there is a corresponding short-term production frontier. The long-term frontier is the envelope from overlapping all the short-term production frontiers for possible infrastructure setting in one graph (Figure. 3-2).

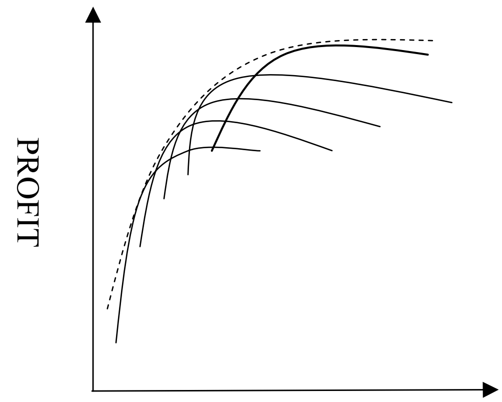


Figure 3-2 Illustration of long-term production frontier (dashed) and short-term production frontiers (solid)

Sediment abatement cost curves can be derived from production frontiers. Assuming the profit reduction from a sediment constraint is considered to be the cost to meet the environmental objective and the point (SY_0, PRO^*_0) is the initial point without sediment control, then the abatement cost curve can be derived using Equation 3-7,

$$C(\Delta SY) = H(SY_0) - H(SY_0 - \Delta SY) \qquad 3\text{–}8$$

where ΔSY is the sediment yield reduction, C(.) is the cost to achieve the sediment yield reduction, H() is the function in equation 3-7. The plot on the right of Figure 3-1 is an illustration of the curve. More accurately, the function, C(.), is a short-term sediment abatement cost curve for a given infrastructure setting in which only variable inputs can be adjusted. A long-term sediment abatement cost curve for a representative ranch can derived from the long-term production frontier. It is impossible to derive all the short-term production frontiers of all possible infrastructure option. This application does not intend to derive long-term production frontiers or long-term abatement cost curves.

In practice, short-term production frontiers and abatement cost curves could be important in two types of applications. The first type of application is to compare different infrastructure alternatives. For any two infrastructure settings, the relationships of two short-term production curves can be crossing or non-crossing (Figure 3-3). The non-crossing relationship implies that one set of infrastructure is better than the other set in the domain where both alternatives have meaningful values. For this case, one infrastructure (upper curve) dominates the other (lower curve). The crossing relationship implies that the ranks of two infrastructures may switch at different sediment control objectives. For example, one set of infrastructure is better than the other at high sediment yield levels, while the order may be reversed at lower sediment levels. For this case, the rank of the two alternatives depends on sediment control objectives.

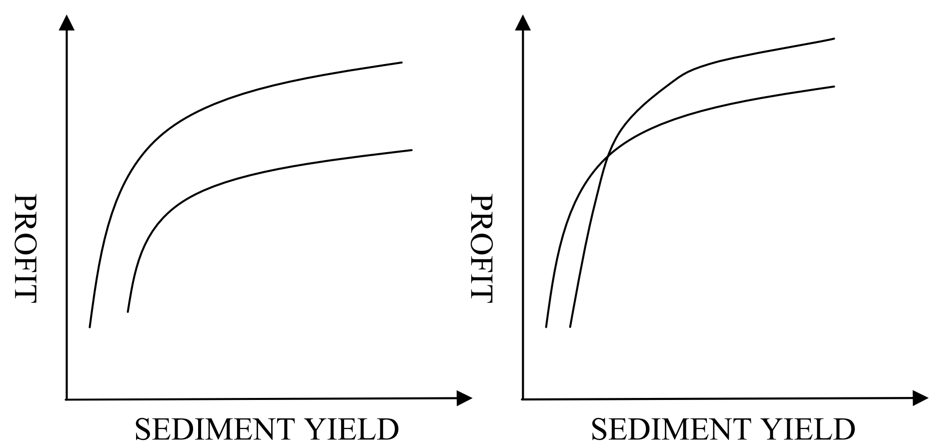


Figure 3-3 Illustration of the relationships of two short-term production frontiers

The other type of application is to assess the effectiveness of a cost sharing policy. When administrators can not directly require ranchers to restrict sediment yield discharge, incentive-based instruments are needed to encourage rancher to participate in soil conservation programs. In Figure 3-4, Curve I is the current production curve, P_0 is the current profit, SY_0 is the sediment yield, and SY_1 is the sediment yield control objective. Assuming the sediment objectives can be achieved by new infrastructure, the new short-term production frontier is Curve II, the increased cost of the new infrastructure is P_0 - P_2 and the increased profit is P_1 - P_2. Since the maximum profit on Curve II, i.e. P_1, is lower than that on Curve I, ranchers are reluctant to adopt the new infrastructure. Administrators can compensate ranchers to participate in the project through cost sharing. A cost-sharing policy may shift the short-term production frontier from Curve II to Curve III. If the maximum profit on Curve III is no less than that on Curve I, ranchers would not reject the new infrastructure.

The level of effective cost sharing depends on several factors. If an infrastructure can improve production and reduce sediment yield simultaneously, the level of effective cost sharing may be less than that of an infrastructure that can only reduce the sediment yield. In some cases, one-hundred percent cost-sharing may not be enough because maintenance is an extra cost for ranchers. The determination of proper cost sharing needs to consider all these factors. The principle for an effective cost sharing policy is that the compensated profits should be no less than that for current operation. In other words, the compensation is no less than difference between P_0 and P_1, as shown in Figure 3-4.

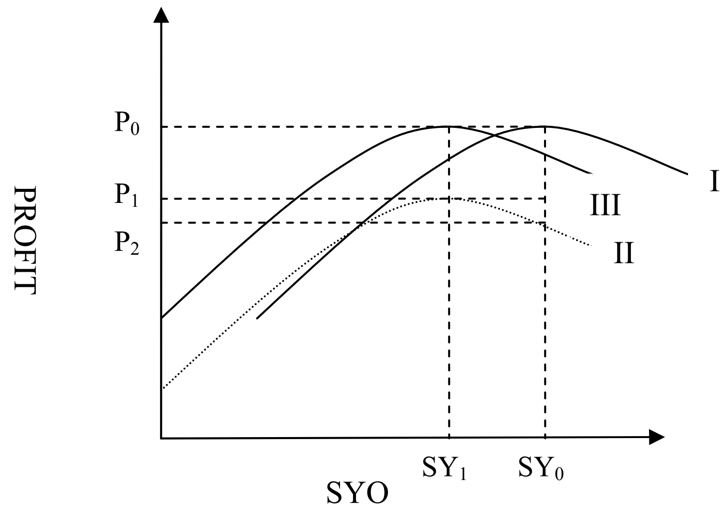


Figure 3-4 Illustration of the impacts of cost sharing policy on production frontiers

The above model can be used in a TMDL analysis. A typical TMDL procedure includes defining management alternatives and selecting the best one from these alternatives. For each management alternative, the model can give a production frontier from Equation 3-7 and an abatement cost curve from Equation 3-8. These curves can be used to compare different management alternatives in a robust way. First, by comparing the production frontiers under the same environmental settings, i.e., same climate and price environment, the curves allow users to define the range over which one management alternative is better than another, which is more reliable than comparison at a point. Second, by making a sensitivity analysis of different parameters, alternatives can be evaluated under different scenarios and the results from diverse analyses provide more confident evaluation of impacts.

The above models do not specify the temporal dimension explicitly yet. However, range processes are continuous and range management impacts may last more than one time interval. By defining temporal structure, the model can be used for short-term or long-term prediction. The selection of a temporal dimension depends on study objectives. To meet the requirements of diverse analysis, this study develops two types of models. The static model is based on long-term equilibrium relationship and is intended to estimate the long-term impacts. The equilibrium model of a range system was first developed by Noy-Meir (1975). This study uses the equilibrium relationship for ranch production. The dynamic model uses differential equations to predict the dynamics of different factors in a watershed.

To apply the model for a watershed application, it is necessary to specify the functions and define the spatial and temporal structures. The model configuration is discussed in Section 3.3. The specifications of equations are discussed in Sections 3.4 and 3.5.

3.3. Model Configurations

Model configurations define the structure of the models. The model has three major types of configurations. The spatial configuration defines how a watershed is spatially segmented to represent the distributions of spatial factors. The temporal configuration defines how a study period is segmented to represent the dynamic characteristics. The component and management configurations define the model components and management types in the model.

3.3.1. Spatial Configuration

Ideally, all the spatial factors should be represented in continuous space. However, it is difficult for most applications since rangelands rarely have enough data to parameterize such functions in continuous spaces. The ‘homogeneous area’ conception is used in many studies (Srivastava et al., 2002; Ancev et al., 2003; Khanna et al., 2003; Veith et al., 2003). This method assumes that there is a way to segment a watershed into many ‘homogeneous units’ that have the same attribute values in each unit. Two approaches are used to define homogeneous units. The first approach divides an area with same land use and/or other properties as a unit. For example, cropland plots are used as the homogeneous units in agricultural watersheds. The other approach splits study area into small uniform grids.

Neither approach is suitable for rangeland watershed studies. The first approach requires that homogeneous units be defined in study areas. Pastures are land use units in grazing lands. However, plant growth and livestock grazing could be significantly varied in a pasture, so pastures cannot be assumed as homogeneous units. The second approach is easily fit into any landscape if using high spatial resolution. However, the number of cells increases exponentially with spatial resolution. For example, the cell number of the Walnut Gulch watershed if split with the 30-meter resolution is about 167,000 units. The number of grid-based units is too large for most NLP optimization solvers. If using one kilometer resolution, the units are too coarse to represent the spatial heterogeneity.

This study uses a method modified from the first approach. The whole study area is segmented into different basic units. The basic units are defined on the two levels. On the first level, basic units are defined by overlaying ecological site and pasture maps, so each basic unit on the first level is in the same ecological site and pasture. One ecological site is aggregated into polygons that have similar potential plant communities and productivity on similar soils, climate and topography. The NRCS developed the database that stores the data for different ecological sites from decades of field measurements. The database provides reliable vegetation data for most rangelands in USA. A pasture is a grazing unit that can be used to control grazing intensity. Consequently, basic units on the first level have similar properties in production and livestock grazing. However, a basic unit is not a 'homogeneous area' since slope, vegetation and grazing may vary at certain levels in a basic unit. Average values of factors in each unit represent the conditions of that basic unit. Figure 3-5 is an example showing how a watershed is segmented into basic units. There are eight basic units on the first level from overlaying three ecological sites, E_1, E_2, E_3, and three pastures P_1 and P_1 and $P_{3,}$ in the sample watershed.

The basic unit on the second level is from overlaying the basic unit on the first level and the sub-watershed systems formed by stock ponds. Ponds are the structures that detain sediment from upstream. An illustration of spatial configuration is shown in Figure 3-5, the three digit number shows all the basic units on the second level, the first digit indicates ecological site type, the second digit indicates pasture code, the third digit indicates sub-watershed code, and 0 in the third digit means that basic unit does not belong to any sub-watershed of a pond. This example only has one subwatershed, S1. The number of basic units on the second level is 10 in this example.

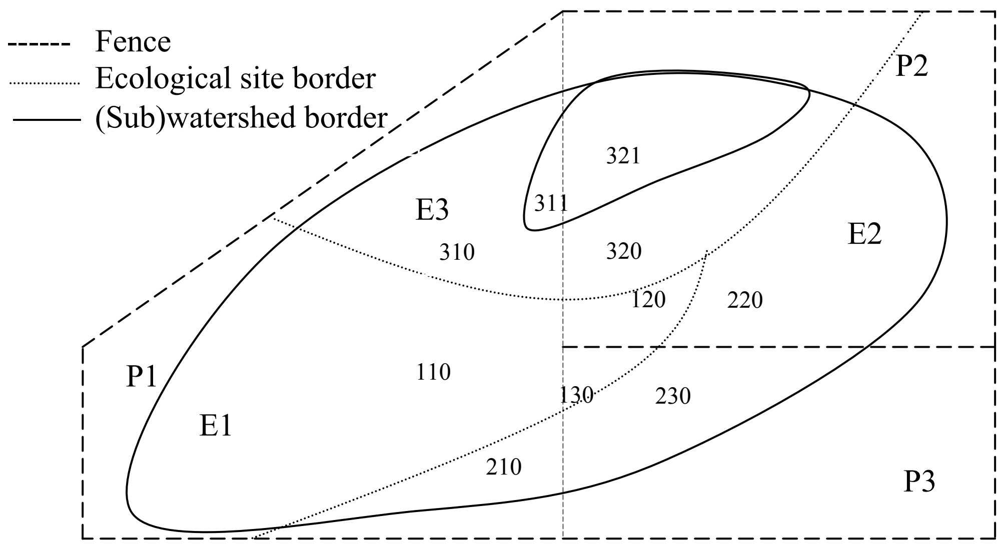


Figure 3-5 Illustration of the conception of basic units

3.3.2. Temporal Configuration

The selection of temporal resolution depends on the study objective. For ranch production, the annual production cycle matches the plant and livestock growth cycles. This study develops two types of models, a static model and a dynamic model. The static model is based on the long-term equilibrium relationship. All factors are based on annual average values. Thus the static model does not explicitly include a temporal index.

The dynamic model uses a temporal index to track the dynamic of different factors. Since seasonal variations are significant in plant growth, hydrologic and erosion processes in southwestern USA, the dynamic model uses seasons as the temporal resolution. This configuration allows the model to track plant biomass and livestock in each season during study period.

3.3.3. Component and Management Configurations

Component-based models are used in many hydrologic and erosion models such as SPUR and WEPP (Carlson, 1993). The advantages of component-based structures includes: 1. compatible with the structure of range ecosystem; 2. compatible with the scientific disciplines; 3. easy to upgrade; 4. easy to integrate different components with different function types into one model.

The models in this study consist of seven components: geospatial factors, climate, plants, livestock, hydrology and erosion, ranch operation, economics and policy (Figure 3-6). However, the models treat the climate and geospatial features as constant and these factors are considered as input parameters. This structure is similar to the component structure of SPUR (Carlson, 1993).

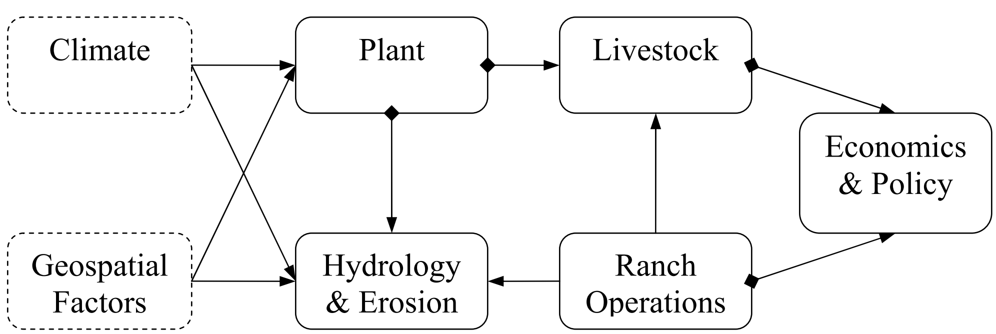


Figure 3-6 Components and their interactions. The lines with diamond tag are the relationships varying with model types.

Each component also includes several factors. These factors are the indicators of rangeland condition and ranch production. The relationships between these factors are represented as the functions in rangeland modeling. The details of these factors in each component and their interactions can be found in Figure A-1 in Appendix A.

Although the NRCS provides a long list of best management practices for rangeland conservation (NRCS, 2004), this study only considers four best management practices, including stocking rate, water points, fences and stock ponds. Stocking rate is a short-term management practice that can be used to adapt to varying rangeland conditions. Water points, fences and stock ponds are the infrastructure of long-term management strategy. Water points and fences are used to control grazing and improve biomass utilization. Although stock ponds could be a temporary water point at some case, this study assumes that the only function of stock pond is to detain sediment. Other BMPs are not considered in this study.

3.4. Specifications of the Static Model

A series of functions are used to represent the relationships in the static model. The different components interact with each other by variables. The major relationships among the components are represented by the arrows in Figure 3-6. The arrow direction shows the cause-impact relationships of two components. The triangular arrow heads are the relationships used in all model options and the diamond-tagged arrows are the relationships only in some model options. The details of the functions in each component are described in following sections.

3.4.1. Climate

Climate is the most important factor in determining carrying capacity of rangeland in the western U.S. Climate fluctuations cause the variation of vegetation production. So ranch management needs to use proper management strategy to adapt to climate variation.

A category-based climate index is used in current range management. In practice, climates for a year are classified into three categories: favorable, normal, unfavorable. The categorized climate is a relative index that is easily understood. And most importantly, current ecological site data are based on this category system. Because the vegetation production in southeastern Arizona is mainly controlled by precipitation, the wet, normal and dry categories are used interchangeably with the favorable, normal and unfavorable categories.

This model includes a parameter for climate condition. The climate directly affects forage production and erosivity. For each climate, the corresponding production and erosion parameters are defined. Users can specify climate type for a year as inputs, and then the production and erosion are predicted based on the specified climate.

3.4.2. Plant

Plants are the key component in range ecosystems. The competition for forage resources between ecological use and grazing is a key issue in range management. The model is intended to aid in selecting the proper forage allocation to different uses to meet the multiple uses in rangeland.

The model defines two types of vegetation, grass and brush. These two types of vegetation have significantly different roles in forage value and soil conservation. Brush has a longer life with large canopy and small basal area. Brush usually has less value in livestock diet. Grass includes annual and perennial grass. Grass has shorter life cycle and high percent basal area. Grass is an important source of livestock diet. Forbs are another type of vegetation in ecological site reports. This study combines forbs into grass type for simplicity. The combination is reasonable for forbs have similar properties in growth and forage value as grass and the percentage of forbs in total vegetation production is usually much lower than grass for most ecological sites in Southeastern Arizona.

Rangeland biomass can be in several states, and biomass is converted between different states in rangeland processes. Figure 3-7 shows all possible states and the conversion relationships used in this study. Biomass production refers to new biomass growth during a time interval. Canopy is the old standing biomass converted from ungrazed biomass production. Litter cover is the dead material on ground decayed from standing biomass. The plant component is divided into two major parts: plant production and biomass conversion. The conversion relationships are described in following sections.

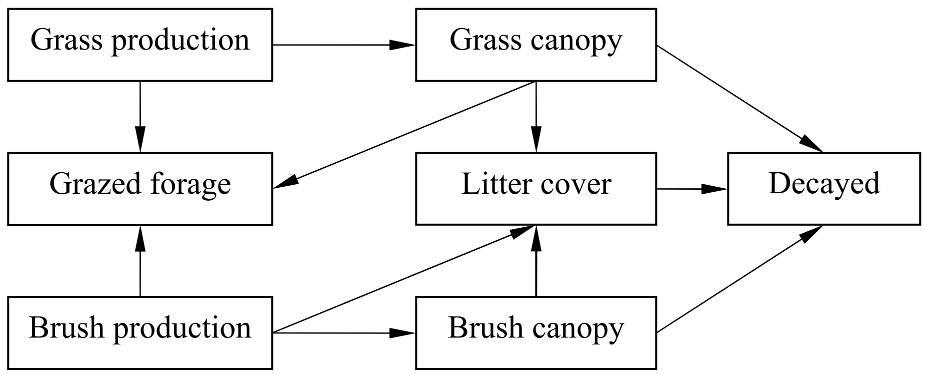


Figure 3-7 Biomass states and conversion in rangeland

3.4.2.1. Plant Production

Vegetation production is the major source of forage and the unique source of all biomass. Several factors may affect the plant production function. The maximum plant production is from the climax production of each ecological site under each climate category. The maximum production is adjusted by ecological condition and climate. The adjusted production is divided into grass and brush production according to the vegetation composition of each ecological site. Then the production for brush and grass is adjusted with the soil productivity index, the SF(*) function in equation 3-9, and forage utilization, the UF(*) function in equation 3-9. Then the plant production functions are:

PRODg = PF(max_prod, climate, eco_site, eco_condition, grass_percent)

* UF(utilization) * SF(soil_potential) 3–9

$$PROD_b = PF(max\_prod, climate, eco\_site, eco\_condition, brush\_percent) \quad 3\text{–}10$$

where $PROD_g$ and $PROD_b$ are the predicted grass and brush production of each basic unit, max_prod is the climax forage production under normal climate of a ecological site, eco_condition is the ecological condition based on the four categories, excellent, good, fair and poor, grass_percent and brush_percent are the composition of grass and brush production in total forage production respectively, utilization is the average grass utilization of each basic unit, soil_potential is the index of soil productivity under certain soil condition, and PF(.), UF(.), SF(.) are the adjusting functions that are described in the following paragraphs. The vegetation data for the ecological sites of MLRA 41 in southeastern, AZ are listed in Table C-2.

The adjusting functions are used to adjust the production based on the value of input factors. PF(.) is the function to define how factors affect the production. The models use climax production for each site as the production capacity, the climax production is adjusted using the ratios of different climate, ecological condition and grass/brush to derive the actual production of brush and grass.

UF(.) defines how grass utilization affects grass productivity. This model supports two types of functions: constant and inverted 'U' functions. The constant function assumes that grass utilization does not affect grass productivity and takes the form, in other words, $UF(.) \equiv 1$. The inverted 'U' relationship assumes that light grazing increases forage production and heavy grazing reduces forage production. The inverted 'U' function was supported by several researchers (Hart, 1986; de Mazancourt and Loreaua, 2000).The function used in this model is:

$$PF(u) = a * U^2 + b * U + c \qquad 3–11$$

where a = -2, b = 1, c = 1. The figure of the function is shown in Figure 3-4.

By selecting different plant growth types, the model can be used for different applications. The relationship is only applied to estimate grass production and the impact of utilization on brush growth is assumed negligible, i.e. grazing does not have any impact on brush production.

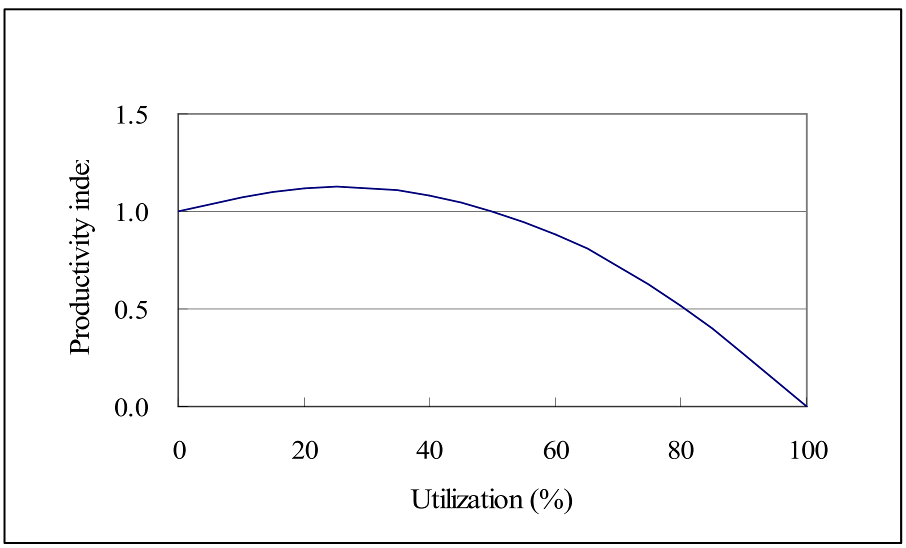


Figure 3-8 Illustration of the inverted 'U' function

The function, SF(.), defines how soil loss affects land productivity. The index, soil_potential, is used to measure the magnitude of soil loss impacts. This study assumes that soil loss does not affect brush or grass production in ecological sites with deep soil.

For ecological sites with shallow soil, soil_potential is multiplied by production to adjust for soil loss impacts, i.e. SF(x) = x. The computation of soil potential is described in Section 3.4.4.4.

3.4.2.2. Biomass Conversion

Biomass can convert between several states (Figure 3-7). The amount of biomass in different states may affect plant production and erosion. For erosion protection, canopy cover and ground cover are the most important factors. The following sections describe the equations to convert these factors.

Canopy Cover

Above-ground biomass provides the first protection of soil from rain-splash. Above-ground biomass includes grass and brush biomass. Brush canopy net increase in a year equals new brush production minus grazed brush. The equilibrium of above ground brush biomass is 20 times annual net brush increase as shown in Equation 3-12. For grass, annual net increase in grass canopy weight equals to annual production minus grazed grass. Assuming that the annual grass decay ratio is constant, Equation 3-13 is used to compute the annual grass canopy. Then total above ground biomass is the sum of brush and grass canopy as shown in Equation 3-14.

$$\text{canopy\_brush\_w} = (PROD_b - GRA_b) * 20 \qquad 3\text{–}12$$

$$canopy\_grass\_w = (PROD_g - GRA_g) / DRgc \qquad 3\text{–}13$$

$$canopy\_w = canopy\_grass\_w + canopy\_grass\_w \qquad 3\text{–}14$$

where canopy_brush_w is the weight of brush canopy, canopy_grass_w is the weight of annual grass canopy, canopy_w is total above-ground canopy, $PROD_b$ and $PROD_g$ are annual brush and grass productions respectively, GRA_b and GRA_g are grazed brush and grass, DR_{gc} is the decay ratio of grass canopy.

Weight of above-ground biomass is converted to a percentage of canopy cover. Canopy cover in percent is an input in computing the RUSLE2 C factor. This study uses the empirical conversion relationship in Equation 3-15. The coefficients of Equation 3-15 are derived from regression of the data in RUSLE2 database.

$$canopy\_p = cb\_w\_p2 * canopy\_w^2 + cb\_w\_p1 * canopy\_w \qquad 3\text{–}15$$

where canopy_p is canopy cover in percent, canopy_w is the weight of above-ground biomass (lb/acre), and cb_w_p2 and cb_w_p1 are the coefficients.

Ground Cover

RUSLE requires ground cover as input to compute the C factor. Ground cover consists of three parts: litter cover, basal cover and rock cover. Litter cover is dead biomass from decayed grass and brush. Basal cover is formed from grass stems. Rock cover is the rock component in surface soil. These factors are important in controlling inter-rill erosion on rangeland (Gutierrez and Hernandez, 1996). The weight of litter is computed from the following equation:

$$litter\_w = (PROD_g - GRA_g) * DR_g + (PROD_b - GRA_b) * DR_b \qquad 3\text{–}16$$

where litter_w is litter in weight, DR_b is annual decay rate of brush, GRAg, GRAb, PRODg, PRODb and DRg have the same meaning as that in Equation 3-12 and 3-13.

The function converting the weight of litter to the percent of litter cover is derived from the data in the RUSLE database for rangeland:

$$litter\_p\ (\%) = -6E\text{-}06 * litter\_w^2 + 5E\text{-}02 * litter\_w \qquad 3\text{–}17$$

The percent of basal cover is derived from grass production. According to the ecological site description MLRA 41, the basal cover is about 18% for 1000 lb/acre grass production. Assuming basal area of grass linearly increases with grass production, the following equation is used to compute basal cover:

$$basal\_p\ (\%) = 0.018 * PROD_g \qquad 3\text{–}18$$

Rock cover provides also soil protection from erosion. In this model, rock cover is assumed to have the same protection as litter cover. The total ground cover is computed through combining litter cover, rock cover and basal area:

$$gc\_t = basal\_p + rock\_p + litter\_p - litter\_p * rock\_p / 100 \qquad 3\text{–}19$$

where gc_t is total ground cover in percent, rock_p is rock cover in percent, litter_p is litter in percent. Since litter cover may overlay rock cover, the last term in Equation 3-19 removes the double counting of ground cover by assuming the litter cover and rock cover are randomly distributed on the ground.

3.4.3. Livestock Grazing

Livestock harvest forage and produce ranch outputs. The livestock component focuses on the grazing process. The livestock output and herd management are described in the next section. Several issues are concerned in livestock grazing. The first issue is grazing distribution. The second issue is grazing equilibrium condition. The third issue is the sustainable grazing constraints.

3.4.3.1. Grazing Distribution

Two approaches are used to predict spatial grazing distribution. The first approach is based on the Range Map method in Guertin, et al. (1998). The Range Map method adjusts carrying capacity of rangeland according to topography and distance to water as proposed by Holechek (1988). Results from this method give an estimation of the highest carrying capacity. This method is simple and easy to implement.

The other approach is based on regression of forage utilization. Compared with Range Map, this method gives smoother and finer grazing distribution. The regression for this study was developed from the data collected on the Santa Rita Experimental Ranch. The function takes the form of:

$$LN(Res) = a_0 + a_1 * SP + a_2 * dist \qquad 3\text{–}20$$

where Res is forage residue, SP is slope in percent, dist is distance to water point, and a_0, a_1 and a_2 are the coefficients from regression.

3.4.3.2. Grazing Equilibrium

Grazing equilibrium describes the conditions to stop grazing. Grazing distribution defines the order or upper limit of forage grazing. Livestock stop grazing when they take enough forage for their requirements. Animal unit months (AUMs) are widely used to estimate forage requirements in range management. AUM is the total forage requirement in dry weight of a cow in one month. The AUM requirements of different livestock are listed in Table C-4 in Appendix C. The grazing equilibrium condition requires that the total grazed forage should meet the AUM requirements of all livestock.

3.4.3.3. Sustainable Grazing Constraint

Just as described in Equation 3-6, the model uses utilization constraints to meet the objectives of sustainable grazing and multiple uses. The model requires that grass utilization for each basic unit is no more than 50 percent of total grass production. Because part of brush is suitable for gazing, brush forage is adjusted by the percentage of grazable forage. And the brush utilization is no more than 30 percent of total production of grazable brush.

3.4.4. Hydrology and Erosion

This study focuses on upland erosion and sediment yield. Upland erosion is predicted by using RUSLE 2. The sediment yield is predicted by combining erosion rate and sediment delivery ratio. Runoff is not explicitly considered in the model.

3.4.4.1. Upland Erosion

RUSLE 2 is used to predict upland erosion. The details of the RUSLE model can be found in Renard et al. (1997). RUSLE is a factor-based model, including six factors:

$$A = R*K*LS*C*P \qquad 3\text{–}21$$

where A is the soil loss in tons per acre of a study plot, R, K, LS, C, P are the RUSLE factors that are described in following paragraphs one by one. To apply RUSLE2 to the computation, the model first derives the values of each factor from inputs and state variables, and then multiplies these factors together to predict upland erosion.

R

R is the erosivity index of precipitation. R values may change in the spatial and temporal dimension. For a small watershed, annual average R values may not be significantly spatially different. In the spatial dimension, the model assumes the same R value for a watershed. In the temporal dimension, R value depends on climate type. R value is positively correlated with precipitation (Nyhan et al., 2001). For a watershed, a lookup table of R for each climate category is used as input.

K

K is the soil erodibility factor. K is used to describe the ability of soil to resist erosion. The model uses a lookup table to map each soil type to a K value.

LS

LS is the geographic and slope factors and can be derived from DEM map in GIS software. This study computes LS using an AML downloaded from Bob's slope page (Hickey, 2003). The AML computed LS factor for each cell based on the procedure in RUSLE handbook. LS values are assumed constant during the whole study period.

C

C is the cover management factor. The value of C depends on the amount of biomass in different states that change with time, location and managements. Vegetation management is a major method to reduce erosion. The computation of the C value of RUSLE includes several steps. This model uses Equation 3-22 to 3-28 to compute a C value. These equations are especially developed for rangeland from Weltz et al. (1987)

with minor changes for unit compatibility. The C value is determined by four sub-factors, as shown in Equation 3-22:

$$C = PLU * CC * SC * SR \qquad 3–22$$

where PLU is the prior land use sub-factor, CC is the canopy sub-factor, SC is the surface cover factor, and SR is the surface roughness factor. These sub-factors can be computed by equations. The PLU sub-factors are computed using the following equations:

$$PLU = (1 - DY) * EXP(-0.012 * RS) \qquad 3–23$$

$$D = 0.55 / T \qquad 3–24$$

where T is the total years over which a soil disturbance diminishes, Y is the years since disturbance, RS is the biomass in the upper 0.1 meters soil in kg/ha. For grazing lands, Y is assumed to equal T. Root biomass could be estimated from Equation 3-25.

$$RS = 0.89 * BIO * \eta i * \alpha i \qquad 3–25$$

where BIO is the annual above-ground biomass in lb/ac, ηi is the ratio of biomass in upper 0.1 meters soil to the total soil biomass. For desert grasslands, ηi is 0.38 and αi is 2.28; for brush lands, the vegetation type is southern desert shrubs, ηi is 0.56 and αi is 1.23.

The canopy sub-factor is computed from Equation 3-26:

$$CC = 1- canopy\_p * EXP(-0.34 * H) \qquad 3–26$$

where canopy_p is the canopy cover in percent, and H is the height, in meters, that rainfall drops after impacting the canopy. In this study, H is assumed to be 0.15 m in grasslands and 0.5 m in brush lands. Canopy_p is from Equation 3-15.

The surface cover factor is computed using Equation 3-27:

$$SC = EXP(-4.0 * gc\_t) \tag{3–27}$$

where gc_t is the ground cover in percent. The ground cover is a combination of litter cover, basal cover and rock cover, and is from Equation 3-19.

The surface roughness factor is computed using Equation 3-28:

$$SR = EXP(-0.026 * (RB – 6) * (1 – EXP(-0.35 * RS)) \tag{3–28}$$

where RB is a random roughness in millimeters and RS is the same as in Equation 3-23. This study use 20 millimeters as the RB value from Renard et al. (1997).

P Factor

The P value is assumed to be one in the model, meaning that no practices are implemented to reduce erosion.

Erosion

Erosion is computed by multiplying these factors together. RUSLE is designed for one slope plot. In the study, each basic unit consists of many different slopes. The study uses average factor values of each basic unit instead of each plot to compute erosion. There is one question of this simplification: could RUSLE be applied on the basic unit level using average factor values? In other words, in Equation 3-29, is the right side equal to the left side?

$$[\Sigma\, T_i * KLS_i * C_i)]/\Sigma T_i = \Sigma(\overline{KLS} * \overline{C}) \qquad 3–29$$

where i is the index of cells in a basic unit, the letters with upper bars is the average value of that factor in a basic unit, T_i is the area of a cell. Beginning from the left side of the equation, each factor can be represented as the mean and a random part, then the left side can be transformed step by step as in Equation 3-30.

$$\begin{aligned}
&[\Sigma\Sigma(T_i * KLS_i * C_i)]/\Sigma]_{\,i} = [\Sigma(\overline{T} + \varepsilon_{1i}) * (\overline{KLS} + \varepsilon_{2i}) * (\overline{C} + \varepsilon_{3i})]/\Sigma T_i \\
&= [\Sigma\overline{T} * \overline{KLS} * \overline{C} + \overline{T} * \overline{KLS} * \Sigma\varepsilon_{3i} + \overline{T} * \overline{C} * \Sigma\varepsilon_{2i} + \overline{T}\Sigma(\varepsilon_{2i} * \varepsilon_{3i}) + \overline{KLS} * \overline{C} * \Sigma\varepsilon_{1i} \\
&\quad + \overline{KLS} * \Sigma(\varepsilon_{1i} * \varepsilon_{3i}) + \overline{C} * \Sigma(\varepsilon_{1i} * \varepsilon_{2i}) + \Sigma(\varepsilon_{1i} * \varepsilon_{2i} * \varepsilon_{3i})]/\Sigma T_i \\
&= [\Sigma\overline{T} * \overline{KLS} * \overline{C} + \overline{T}\Sigma(\varepsilon_{2i} * \varepsilon_{3i}) + \overline{KLS} * \Sigma(\varepsilon_{1i} * \varepsilon_{3i}) + \overline{C} * \Sigma(\varepsilon_{1i} * \varepsilon_{2i}) \\
&\quad + \Sigma(\varepsilon_{1i} * \varepsilon_{2i} * \varepsilon_{3i})]/\Sigma T_i \\
&= [\overline{KLS} * \overline{C} * \Sigma\overline{T} + \overline{T}\Sigma(\varepsilon_{2i} * \varepsilon_{3i})]/\Sigma T_i
\end{aligned} \qquad 3–30$$

where ε_{1i}, ε_{2i}, and ε_{3i} are the random part of each cell. From the definition, $\sum\varepsilon_{1i} = 0$, $\sum\varepsilon_{2i} = 0$, $\sum\varepsilon_{3i} = 0$, so line 2 in Equation 3-30 is transformed to line 4. Since grid-based cells have uniform area, which means $\varepsilon_{1i} \equiv 0$, then line 4 is transformed into line 6. The only term that may cause bias is the correlation between KLS and C among cells in a basic unit. Because C value changes with management and landscape, it is difficult to prove if there is a correlation between KLS and C or not. However, from the definition of a basic unit, each cell in the same basic unit has the similar KLS and vegetation condition, then ε_{2i} and ε_{3i} should be small. So even if there are correlations among these two factors, the bias may not be very significant. However, further proof may be needed in future study.

3.4.4.2. Sediment Yield

Sediment yield is the total amount of sediment that flows through a watershed outlet during a certain time interval. Sediment yields depend on erosion sources and transportation processes. Sediment sources include upland and channel erosion. Transportation processes determine how much sediment is transported downstream. The dynamic property of transportation processes implies that sediment yield depends on initial states and intermediate processes in a given interval. For long-term management purposes, the long-term average impacts of practices are more concerned. The model assumes that there is a ratio between the induced sediment yield increase and the upland erosion increase for each cell. As illustrated in Figure 3-19, if the upland erosion of a cell increases at time T_0 and continues for a long time while keeping all other cells the same, the sediment yield at the outlet increases gradually and reaches the equilibrium at T^*, then the coefficient is defined as $\Delta SY^*/\Delta E^*$.

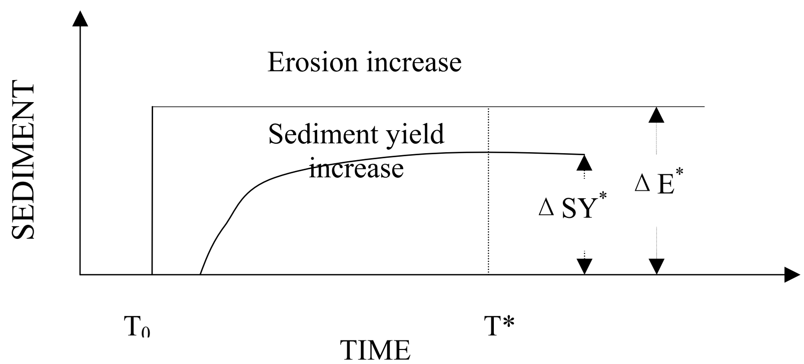


Figure 3-9 Illustration of sediment yield coefficient for one cell. If the erosion in a cell increases at time T_0, the sediment yield at outlet increases and reaches the equilibrium at T^*, then the coefficient for the cell is $\Delta SY^*/\Delta E^*$.

Although the conception of a coefficient is simple, most watersheds do not have sufficient data to derive the value. Some approximations may be used. For example, if there is a calibrated distributed erosion model for a study area, the coefficients can be approximated through long-term simulation results. However, few watersheds have such models. Another method is to use a cell–based method. A SDR is derived through expanding from cell to area. A similar method was used in Veith et al. (2003). The case study uses this method, the details can be found in Section 5.2. If there is a better way to define a delivery ratio layer for a watershed, the new data can be incorporated the model easily. This study uses a SDR map as input and the SDR map is used to derive an average SDR for each basic unit.

The predicted sediment yield is adjusted with pond deposition. The model assumes that all the sediment from the sub-watershed of a working pond is detained. Pond capacity for each location is used as initial inputs. Pond life is defined as the average time filling a pond. Dredging is implemented when a pond is full of sediment.

3.4.4.3. Sediment Control Constraints

The sediment yield control objective is defined as a constraint that requires the total sediment yield to be less than the control objective. In a project, a sediment control objective is defined under normal climate. Since climate types may affect the precipitation and runoff, the objective is adjusted proportionally with R values. In wet years, more sediment yield is allowed than normal because of high runoff.

3.4.4.4. Soil Potential Index

The direct impact of soil loss is the reduction of upland soil depth. Deep soil can hold more soil moisture, which is a limiting factor of plant growth in southwestern USA. Soil erosion reduces water holding capacity and thus reduces productivity. This model uses a soil potential index to represent this impact.

The soil potential index is computed based on several assumptions. The model assumes the average soil depth in shallow ecological sites is 0.1 meter. One ton per acre of soil loss corresponds to around 0.11 millimeters of soil depth. For 20 years, the reduction in soil depth is two percent for one ton per acre per year of soil loss. Assuming a linear relation between soil and productivity, one ton per acre of annual soil loss would cause two percent of productivity reduction in 20 years. On the other hand, the model assumes soil natural regeneration is at a constant rate, 0.00056 m/year or 0.56 ton/acre/year (Cooper, 2000). The impact of soil loss on ecological sites with deep soil is assumed to be zero. The soil index of ecological site with shallow soil is computed with Equation 3-31:

$$\text{soil\_potential} = 1 - 0.02 * (\text{erosion} - 0.56) \qquad 3\text{–}31$$

where soil_potential is a unit-less index, and erosion is annual erosion in tons per acre.

3.4.5. Ranch Operation

This study uses a cow-calf ranch operation, the typical ranch type in southern Arizona. The static model uses herd size and the number of breeding cows to represent the scale of ranch operation, and the number of other types of livestock is derived through herd structure ratios. The conversion relationships of livestock types are shown in Figure 3-10. The herd size is the total number of cow/calf pairs in a ranch. The number of bulls is proportional to the herd size. In each year, a certain percentage of cows bear calves and some of the old cows are culled for sale. At the end of each year, some heifer calves are kept as yearlings to maintain the herd size and other calves are sold for revenue. All culled cattle are sold at the end of a year. The conversion ratios in this study are from Teegerstrom and Tronstad (2000) with several exceptions. First, this model assumes that all calving occurs in the spring. Second, the ratios of heifers kept and cows culled are adjusted to keep a stable herd size. Third, some herd management issues, such as lost livestock or death, are ignored in the model.

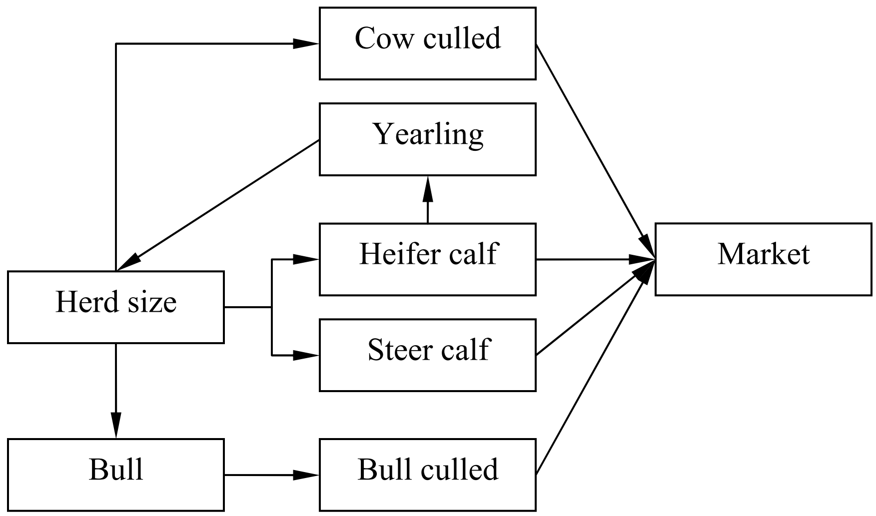


Figure 3-10 Herd structure and the conversion relationships of a cow-calf system

3.4.6. Economics and Policy

The economic component uses a monetary unit to measure all inputs and outputs of ranch production. Profit maximization is defined as the overall objective for assessing the efficiency of ranch production. Profit is the net income defined as total revenues minus total costs.

Ranch revenues are from the sale of different types of livestock. As shown in Figure 3-10, all types of livestock with arrows pointing to the ‘market’ box create revenues of a ranch. Total revenues are the sum of all sale revenues from marketable livestock.

Ranch costs are divided into two categories: variable and fixed costs. Fixed costs are the long-term investments, such as infrastructure, equipment, livestock, and so on. Most fixed costs are related to ranch size. This model defines a fixed cost for ranches with standard size ranch. The actual fixed costs are adjusted proportionally with ranch size. The reproductive livestock are computed separately from other fixed costs. Since the life of infrastructure is usually longer than the study period, the annualized fixed costs are computed from the life time fixed cost. For all productive livestock input and new infrastructure inputs, annualized fixed cost is computed through Equation 3-32 (Coats et al., 1998):

$$A_{CR} = \frac{(PPC - \frac{SV}{(1+r)^N})}{(\frac{1 - \frac{1}{(1+r)^N}}{r})} \qquad 3\text{–}32$$

where A_{CR} is the annualized cost of a fixed input, SV is salvage value, PPC is total pre-productive cost adjusted to the first productive year, r is real interest rate, and N is the total life of project life. Variable costs include many items, as listed in Teegerstrom and Tronstad (2000). This study combines these items into thee types of costs: feed cost, other cost and financial cost. Each variable cost is computed from the annual cost per herd times herd size.

Cost sharing variables are also included in the model. A cost sharing policy was used by public agencies to aid ranches to invest in range improvement infrastructure. Different levels of sharing can have great impacts on the economic status of ranches. In this model, the cost shared through cost sharing policy is deducted from fixed cost.

3.4.7. Summary of the Static Model

The static model is an optimization problem integrating bio-physical functions, resource constraints and the ranch management objective. The framework of the model is given in Equation 3-6. Section 3.6 describes the details of each function. The model are summarized also in the Table 3-1.

Table 3-1 Summary of the structures of the static and dynamic models

<table>
<tr><th colspan="2">Item</th><th>Static</th><th>Dynamic</th></tr>
<tr><td rowspan="4">Configuration</td><td>Temporal</td><td>One year</td><td>Four seasons * planning years</td></tr>
<tr><td>Spatial</td><td colspan="2">Basic Units</td></tr>
<tr><td>Management</td><td colspan="2">Grazing Intensity / Water point
Fence / Stock pond</td></tr>
<tr><td>Vegetation type</td><td colspan="2">Grass / Brush</td></tr>
<tr><td colspan="2">Objective</td><td>Maximize profit</td><td>Maximize profit NPV</td></tr>
<tr><td colspan="2">Decision Variables</td><td>Annual grazing at each unit
Erosion rate
Herd size</td><td>Seasonal grazing at each unit
Erosion rate
Herd size</td></tr>
<tr><td rowspan="3">Bio-Physical Model</td><td>Climate</td><td colspan="2">Category-based</td></tr>
<tr><td>Plant Growth</td><td>Annual Climax adjusted with factors</td><td>Seasonal climax adjusted with factors</td></tr>
<tr><td>Grazing</td><td colspan="2">Range map or regression equation</td></tr>
</table>

	Grazing equilibrium	AUM demand = Foraged grazed	
	Biomass Conversion	Equilibrium equation	Difference equation
	Erosion	RUSLE2 and SDR	
	Ranch operation	Cow-calf system	Cow-calf-yearling system
	Economics & policy	Annual profit	Profit NPV of plan years
Constraints	Utilization	Grass utilization <= 50% at each basic unit Brush utilization <= 30% at each basic unit	
	Sediment yield	Sediment yield less than defined control objective	

3.5. Specifications of the Dynamic Model

The dynamic model has the same component structure as the static model. There are several major differences between the static and dynamic models. A comparison of the two models is listed in Table 3-1. The dynamic model is intended for multiple year planning. For the plant and livestock components, a season-based temporal structure is used to represent the seasonal variation. The dynamic model can track the dynamics of biomass and livestock herd. This section uses the same structure as in the previous section to describe these differences between the static and dynamic models.

3.5.1. Climate

The dynamic model still used the three category climate type, i.e. wet, normal and dry types. Unlike the static model only has one climate type for a project, the dynamic model can define one climate type for each year of the planning period.

3.5.2. Plant

The dynamic model makes three major changes in the plant component. The first change is that plant growth is season-based. The annual production is divided into the production of four seasons based on the growth curves. The factors that affect the plant production are the same as in the static model. The second change is the biomass conversion relationships. The conversions among different biomass states are made at each season. Unlike the static model, ungrazed production at the end of each season is converted to grass canopy at the end of each season. Biomass decaying is computed in each season instead of annually decaying in static model. The third change is that the canopy biomass and litter biomass are based on the dynamics of biomass conversion:

$$Bio_t = Bio_{t-1} - New_t - Con_t \qquad 3\text{–}33$$

Where Bio_t and Bio_{t-1} is the amount of biomass of a state at the end of season t and t-1, New_t is the new added biomass during season t, Con_t is the consumed amount during season t. The new added biomass could be new production or converted from other states. The consumed biomass could be grazed or converted into other biomass states. The grazed biomass is from the livestock grazing equation. The biomass converted to other states is predicted using seasonal decaying ratios.

3.5.3. Livestock

Livestock grazing in each basic unit is computed in each season. The total grazed forage should meet the forage requirements of livestock in each season. Livestock may graze three types of forage: new grass production, new brush production and dead standing grass. The grazing constraints are season-based. The utilization constraints require that the utilization of new grass production should be no more than 50%, the utilization of new brush production should be no more than 30% of the grazable brush production, and the utilization of dead standing grass should be no more than 30% of the total amount forage at the end of last season.

3.5.4. Hydrology and Erosion

The erosivity, i.e. RUSLE R factor, in Southeastern Arizona is mainly caused by summer storms, as are runoff and sediment yield. Since most erosion and sediment yield occurs during summer, the dynamic model only computes erosion and sediment yield during summer. The C value is computed from a weighted average of canopy cover and ground cover of before and after summer. The weight is two thirds for the value before summer and one third for the value after summer. The computation of erosion and sediment yield is the same as in the static model.

3.5.5. Ranch Operation

The dynamic model uses a more flexible ranch management system, specifically a cow-calf-yearling system. A cow-calf-yearling system allows ranchers to keep more calves in favorable years when there is more forage. The relationships of conversion between different livestock types are shown in Figure 3-11. The solid arrows indicate that these relationships are the same as those of cow-calf operations in the static model. The dashed arrows indicate the special relationships of a cow-calf-yearling system in the dynamic model.

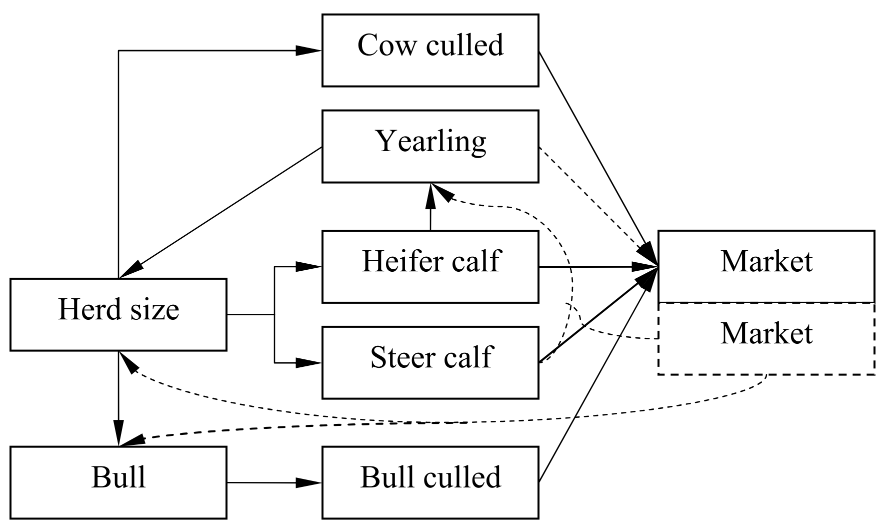


Figure 3-11 Herd structure and conversion relationships for a cow-calf-yearling system

3.5.6. Economics and Policy

In the dynamic model, several modifications are made in the economic components. First, the model considers all yearlings as revenues. Since all herd inputs are counted as fixed cost and counted in annual costs, this approach can prevent unnecessary change of herd size under normal conditions. Second, the dynamic model adjusts herd size year by year according to available forage. By adding adjustment cost, the changes of herd size are made only when the forage resource is scarce. Third, the objective is to maximize net present value (NPV) of profits for the whole planning years.

3.5.7. Model Initialization

The dynamic model requires initial conditions of biomass and livestock herds. The model supports two methods for initialization. The first method uses observed data if such input data exist. The second method adds the constraints that require the biomass and herd at the end of study period to be equal the initial values. The second method is based on the concept of sustainable grazing and is used in the case study for Walnut Gulch Watershed because no detailed vegetation and herd data are available.

3.5.8. Summary of the Dynamic Model

The dynamic model can be used to optimize grazing with sediment yield control in a multi-year period. The dynamic model used season as the temporal resolution to track seasonal variation of biomass and grazing. The years that the dynamic models predicted depend on the available computer resources and the required. The more years to predict, the longer time is required. A summary of dynamic model is also listed in Table 3-1.

3.6. Model Solution

The above models are nonlinear optimization problems. There is no general algorithm to solve nonlinear problems. This section discusses two issues with model solution. The first is the local optimum and global optimum. The second is the GAMS code to solve the models.

3.6.1. Local Optimum vs. Global Optimum

Solutions from solving NLP are local optima if feasible solutions exist. Under certain conditions, such as for convex planning problems, a local optimum is also a global optimum. This study uses GAMS to derive the local optimum. In the sample study, different initial values were used in GAMS code and the solution is the same. In addition, all solutions from the case study are within the reasonable range. The local optimum from GAMS solution is assumed to be the global optimum of the problems.

3.6.2. GAMS Program for Solving Models

The General Algebraic Modeling System (GAMS) is a high-level computer language for solving mathematical programming and optimization problems (Brooke et al. 1998). It separates model presentation and solution algorithm. This separation allows users to focus on constructing proper model structures. GAMS will select the proper solving algorithms through different solvers. Users can select different solvers to solve their problems.

This study uses GAMS to code and solve the static and dynamic models. The code was created in the GAMS editor. For the SDSS application, the code is split into three parts. The first part includes the input parameters and is created dynamically from a database. The second part includes variable definitions and equations. The third part includes a solver, solving procedure and output format. These three parts are assembled into a complete GAMS program for a specific application on-the-fly in the SDSS. The GAMS code is listed in Appendix B. This study uses two NLP solvers, CONOPT3 and MINOS.

3.7. Model Parameterization

A series of parameters are required to construct the static and dynamic models. According to the spatial scale at which a parameter is applicable, parameters can be classified at four levels: global, regional, watershed and scenario. The global parameters are the parameters that have the same value for any area. The regional parameters are only suitable for a region and the value may change in different climate zones or ecosystem regions. The watershed parameters are the parameters that only apply to a specific watershed. The scenario parameters are specified for a scenario and may vary scenario by scenario within a watershed.

The global and regional parameters are embedded in the models and these parameters are transparent to users. Most coefficients in model specification are of these types. The watershed parameters are set when adding a new watershed to the system. The scenario parameters are the parameters that users can control. User analyses are mainly performed through adjusting scenario parameters.

3.8. Model Extension

Model extensions include analysis, watershed, and function extension. The analysis extension is to add new analysis functions over the basic model. Watershed extension is to apply the new watershed to current model. The function extension is to add the new relationships to current models.

3.8.1. Analysis Extension

By creating a series of optimizations in one execution, GAMS allows more advanced analysis. For example, sensitivity analysis can be performed in one GAMS program to perform sensitivity analysis for different factors. By setting the target parameters at different values, sensitivity analyses assess the impacts of different parameter value on the objective. Another example is to compute a production frontier and abatement cost curve by setting different sediment yield levels. These two example applications are created for the SDSS. The code can be found in Appendix B.

3.8.2. Watershed Extension

Watershed extension can be routinely implemented if new watersheds have the same regional parameters as the current system. By setting new watershed parameters, the model can be run for new watersheds. If new watersheds require new regional parameters or functions, then the extension may be implemented through function extension that is described in next section.

3.8.3. Function Extension

Function extensions include two types. The first type is that the change is only made to coefficient values. The second type is that the change is made to the functional form and coefficients. The first type of extension is easily implemented by updating regional parameters. The second type change is generally more difficult. It may require both rewriting the code and new parameters.

3.9. Summary

This chapter provides complete descriptions of two economic models of sediment control in rangeland watershed. The models are component-based models. The spatial characteristics are represented through basic unit structure. The models include static model and dynamic models. The results from the models can be used to compare infrastructure and grazing management.

To implement the models, a lot of parameter inputs are required. Some inputs can only be derived through complicated geospatial analysis. The management of inputs and outputs are also challenging. The interpretation of results require of GIS and other visualization techniques. An SDSS is desired to provide a platform through which users can make their analysis with little experience in geospatial analysis and simple computer device. The next chapter describes the construction of such a system that meets these requirements.

CHAPTER 4 SDSS DESIGN AND IMPLEMENTATION

The economic models in Chapter 3 may be difficult to implement for many users. The models require a lot of spatial and non-spatial data for parameterization. Users need to purchase hardware and special software, and also need experience in geo-spatial analysis and optimization modeling. Furthermore, users need experience in different processes, such as data preparation, spatial analysis, model execution, and result visualization.

Many users cannot meet these requirements to implement their watershed management. Desktop-based applications by different users may also cause other problems. For example, different users have to collect the same data individually, and model upgrades need to be done for each application. Thus desktop-based applications cause redundancy in data repository, hardware and human resources. The redundancies in data storage and collection may further cause data inconsistency and reduce investment efficiency.

A web-based SDSS provides an alternative to avoid these problems. A web-based SDSS uses a central web server to provide a shared analysis platform for users. The system can provide services of data management, model execution and result visualization. Since the system is hosted on a server, upgrading the system or part of the system is fast and simple. The web-based system provides easy access since the access of such system only requires a web-browser and the internet connection, which are now widely available.

This chapter describes the details of SDSS design and implementation. Section 4.1 summarizes the SDSS framework, including system requirements and the architecture. Section 4.2 describes the interface design and implementation, including dynamic web-pages, map browser and editor. Section 4.3 describes the database design and implementation. Section 4.4 describes the system integration of middleware, geospatial analysis and optimization models. Section 4.5 defines use cases that the SDSS supports. Section 4.6 discusses the possible extensions of the SDSS. The final section summarizes this chapter.

4.1. Framework

4.1.1. Requirements

The objective of this SDSS is to develop a system that allows users to perform an analysis of sediment control on rangeland watersheds through a web application. Several requirements are defined to meet this objective. The first is the data management requirements. The system should support the management of various data sets, embedded and user-created, including both spatial and non-spatial data. The database is expected to relieve users' burden of data management. The system should also allow users to create their own spatial and non-spatial data and separate user-specific data from other users'. The second is the interface design requirements. The interface should support data editing and model analysis through a web browser. The system should provide a map editor for editing three types of BMPs, fences, water points and ponds and a map browser for viewing spatial layers. The interfaces should also support result visualization in the form of tables, graphs, and maps. The third is the system integration requirements. All spatial analysis, data management, model execution, and result visualization should be transparent to users. Users can select their inputs and action by simple actions, such as clicking or simply typing, and then the system should automatically execute the analysis. The fourth is the help system requirements. The system should provide several help methods to guide users through the analysis and solving possible problems in implementation.

4.1.2. SDSS Architecture

The web-based SDSS uses a client-server model to communicate between users and the SDSS servers. More specifically, the client/server model takes a three-tier architecture (Figure 4-1). The three tiers include the interface, process and data tiers. The interface tier, also called presentation tier, is to provide user services to manage the session, inputs and display. Users can activate events and issue requests to the servers through these interfaces. The servers are the ports through which the SDSS provide services. There are two types of servers to serve the web page. The web page server provides dynamic pages of text, figures and tables. The map server provides the map-based web page.

The process tier, also called the middle tier, contains all middleware that provides the communications between web pages and application processes that specify the detailed implementation for each application. This SDSS includes two major applications. The first applications are GAMS programs to optimize NLP of watershed management. The other applications include the ArcGIS AML codes to make geospatial analysis.

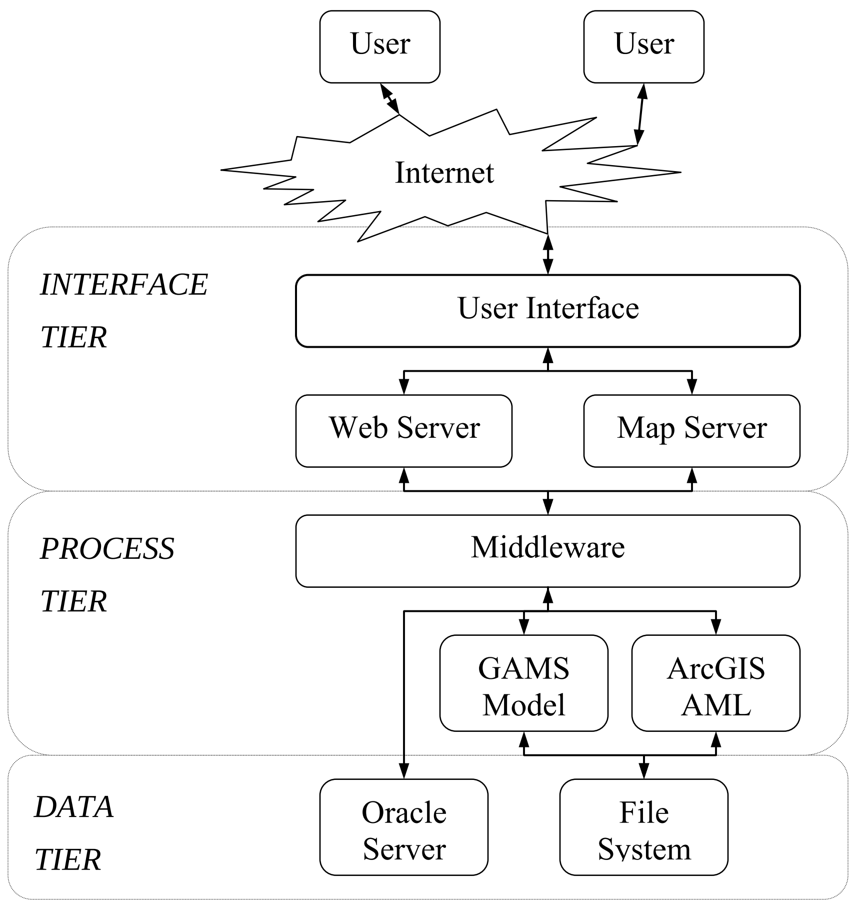


Figure 4-1 Architecture of the SDSS

The third tier is the data tier. This SDSS uses two types of data storage, the database and files. The Oracle database server is used to manage non-spatial data in this SDSS. Part of the data, mainly spatial data, is stored in the file system. The communication between GAMS and the database is through the file system. The geospatial analysis code and spatial layers are also stored in file system. The management of files is through the database and middleware.

Although the Oracle database supports spatial data, this study uses the shape files to store most layers. The main reason is that ArcInfo AMLs do not support geospatial spatial data and database connection. Using the shape files removes the process to convert spatial data from database to GIS map files before activating an ArcInfo AML process. The shape files in the local server accelerate the response time of MapServer.

4.1.3. Functionality and Analysis Flow

The functionality in a DSS mainly depends on the study objective. The functionality implemented in a system can affect interface design, database design, and potential user groups. This SDSS includes four major types of functionalities, user management, scenario management, project execution and result visualization. The user management functionality manages all users' information and tracks user's activity. The SDSS supports users' registration, login and logout to customize users' applications. The web pages are customized according to a user's analysis. User's identification allows the SDSS to balance data sharing and customized applications.

The input management functionality provides several methods to create, view and manage users' inputs. Users can view existing data, create new sets of data and delete their own data. The inputs include price and cost values, pasture management, pond management, climate, ecological condition, sediment control objective and cost sharing.

Besides supporting textual data management, the system also provides a map browser to view spatial layer and a spatial editor to create new geospatial layers such as fence, pond and water point layers.

The project execution functionality allows watershed analysis through embedded models. Users can select the type of analysis. Then model execution is automatically activated and results are saved back to the database. The result visualization functionality supports several methods to view results, such as listing results in tables, drawing results in figures to show the trend and displaying spatial results in a map. Through the diverse result outputs, users can easily understand results and create proper reports for their application.

The flow chart of the SDSS shows the functionality and the procedures of typical analysis (Figure 4-2). The functionalities are organized in two levels. The vertical boxes are the groups of functions of one topic and the horizontal box corresponds to a function to implement a certain operation in a group. The arrows show the order to make the analysis. After login, users first need to create or edit inputs. The project function assembles different inputs into an analysis project. Then the project can be executed. Furthermore, results from project executions are stored in the database and could be viewed any time after running.

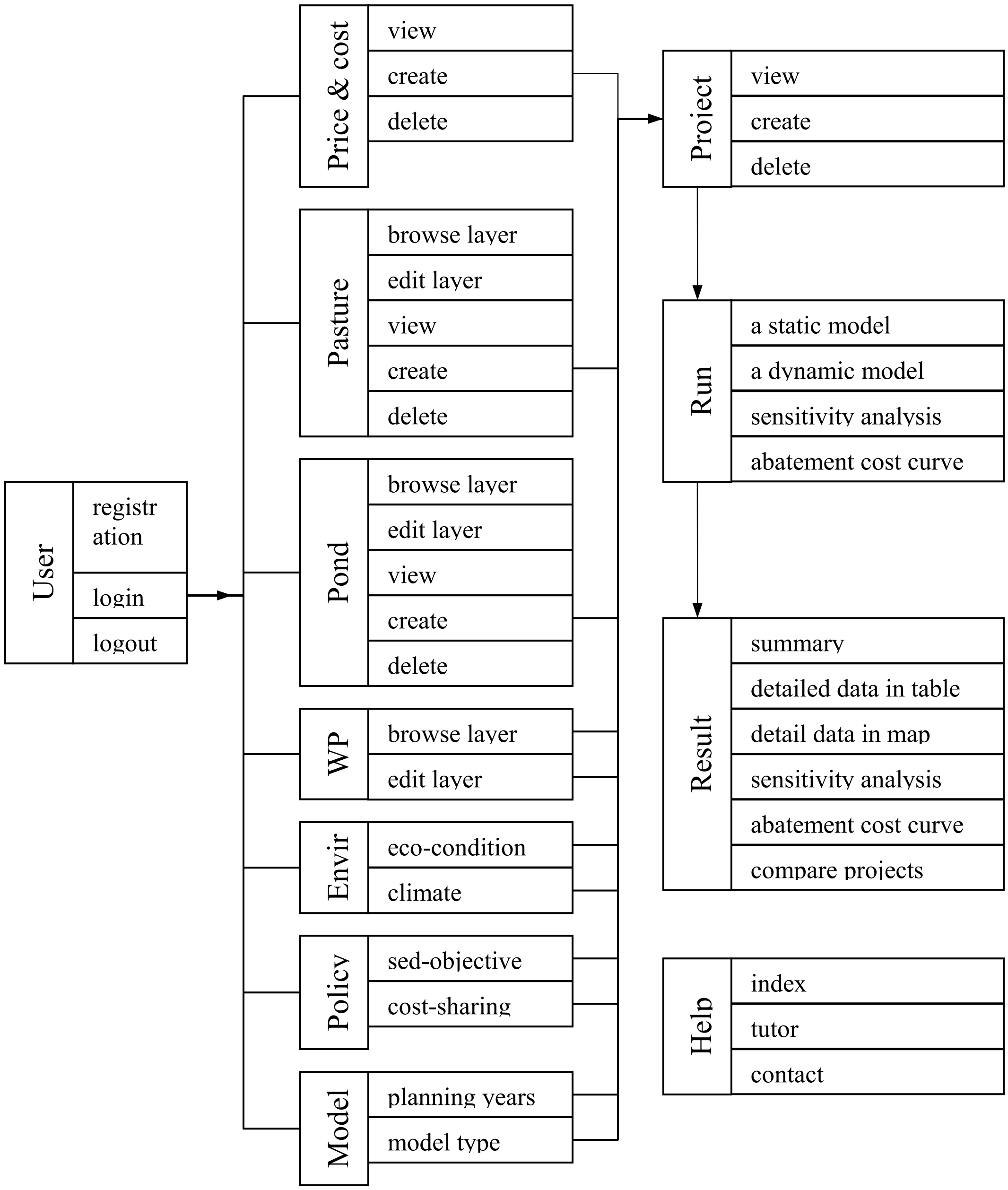


Figure 4-2 SDSS analysis flow chart

4.2. Interface Design and Implementation

The interfaces of a SDSS provide the link between users and the analysis models. A well designed interface would help users in making analyses and presenting results efficiently. The interface design is especially important for the applications intended for inexperienced users. In this study, the interfaces are a series of customized web-pages that allow the users to create inputs, run models and view results.

The web pages are the digital media to convey information on the Internet. A web page can take diverse formats to present information. Web page designs need to select the best combination of techniques to present their information. This SDSS uses state-of-the-art technology to create interactive and customized web pages.

4.2.1. Web Page Design Technology

Several web techniques are used to create the web pages. Most of the web pages are dynamic web pages created on the fly. This SDSS uses three major techniques to create dynamic web-pages: JSP/Servlet, JavaScript, and MapServer.

JSP/Servlet

Java Server Pages (JSP) and Servlets are the server-side technology for creating dynamic web page on the Java 2 Platform. The details of the technologies can be found at *http://java.sun.com/j2ee/*. The basic structure of a JSP/Servlet includes a container and application codes. The container used in this SDSS is Tomcat 4.1. In this study, JSP and Servlets are also used with Java Database Connectivity (JDBC), Java Beans and session management to create customized web pages.

JavaScript

JavaScript is mainly client-side dynamic web page technology and the details of the technology can be seen in Flanagan (2002). Client-side JavaScript can implement minor operations on client machine, thus the response is fast. The combination of server-side JSP/Servlet and client-side JavaScript can help to create customized web pages to support diverse functionality for user access.

MapServer

MapServer is a CGI-based web server. It is simple and supports the major functionality of web map publishing. A MapServer application includes map files and server program. The MapServer can reside in other web pages that allow more efficient presentation of maps and allow users' interaction. MapServer, combined with dynamic web page technologies, can create customized map and html files on the fly to display customized maps.

4.2.2. Interface Implementation

Page Layouts

Each web page in this SDSS includes four sections (Figure 4-3). The top section includes the SDSS logo. In the middle sections, the menu system is on the left column and the major contents of the web pages are on the right column. The bottom section displays additional information about the system. In the middle sections of a map browser page, map images are on the left column and tool/legend section is on the right column.

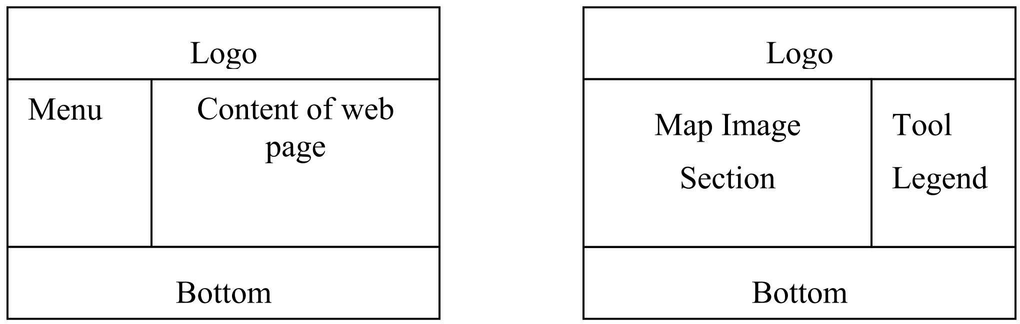


Figure 4-3 Web page layouts. (left: JSP/Servlet page; right: map browser/editor).

Menu System

The menu system is used to provide neat organization and quick access of different web pages. Compatible with the functionality, this SDSS uses a two level menu structure (Figure 4-4). The first level menu lists the function groups, and the second level menus list all web page /functions in each group of the first level menu. The menu system was created using Cascading Style Sheets (CSS). The menu system is displayed in each JSP web page. The two-level menu structure allows users to access other functionality at no more than two steps. In following sections of this chapter, the commands using menus are represented as capital letter and two level menu are separated from the first level menu by '|'. For example, PROJECT|VIEW means that the view action under Project main menu.

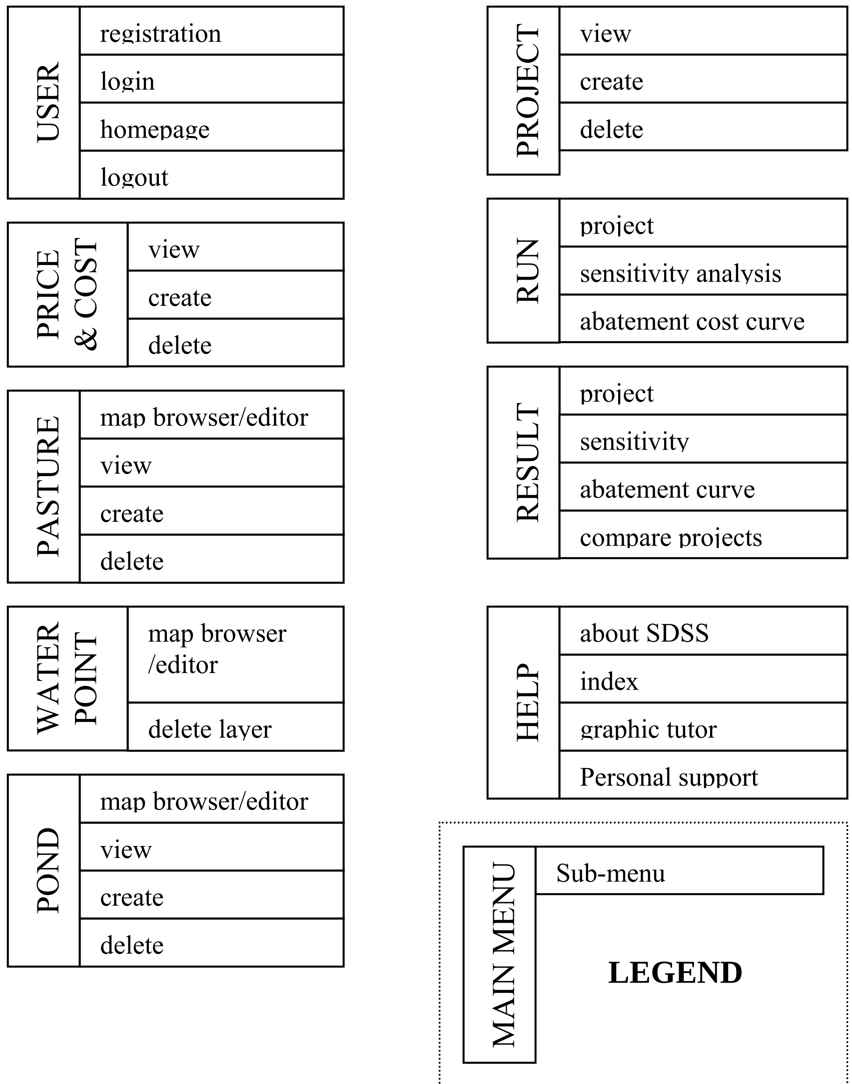


Figure 4-4 SDSS menu structure

JSP Pages

The web pages are customized for both watersheds and users. The watershed selection page lists all available watersheds that the SDSS supports and users can select the watershed that they are interested in to start analyzing. The login page provides user identification. The user registration page allows users to create new accounts. After selecting a watershed and logging in, users can begin their analysis by navigating through the customized web pages. The screenshot of the major web pages can be found in Appendix G.

The HOMEPAGE is the first page that users see after logging in. This page provides the introduction to the SDSS and allows users to turn on/off the tutor help system, which graphically indicates the progress of an analysis. From the home page, users can access other pages through the menu system.

The PRICE & COST main menu includes three JSP pages, viewing a price scenario, creating a scenario and deleting a price scenario. The VIEW page provides a list of scenarios that are currently available for a special user. The CREATION page allows user to create a price and cost dataset that inherits data from the current template. The DELETE page allows users to delete existing price and cost datasets.

The data related to spatial managements are managed through three main menu items: PASTURE, WATER POINT and POND. Each of the three major menus can edit and browse spatial layers. The map browser is used to view certain layers interactively. The map editor is used to create new spatial layers based on the current layers. For pasture and pond layers, management scenarios of spatial infrastructure can be defined through the CREATE MANAGEMENT SCENARIO page. After creating a layer, users can define a management system over that pasture or pond layer. The pasture management defines if a pasture is grazed or not. The pond management defines if a pond is used or not in a management scenario. Management scenarios of pasture or pond can be viewed or deleted through the VIEW or DELETE submenu item respectively in the PASTURE or POND menus.

The PROJECT main menu is used to manage projects. A project is a group of scenario specifications including a price and cost scenario, pasture layer, pasture management, water point layer, pond layer, pond management, sediment control objective, planning span, ecological condition and model type. Defining a project is a process to assemble different input scenario into a project. Users can create a new project in the PROJECT|CREATE page. Several inputs can be selected from option lists, and other inputs may need users to type corresponding values. Users can also view or delete existing projects through PROJECT|VIEW or PROJECT|DELETE submenu.

The RUN main menu provides the interfaces to allow users to run a project in a different mode. The analysis types include running a project, running a sensitivity analysis and calculating an abatement cost curve. In each running, users can select a project, specify the climate and analysis type then click the RUN button to execute a model. For multi-year projects, the pages provide a list of climate options for each year.

The RESULT main menu provides several types of output presentation for different types of analysis. Users can view the summary and detailed results of a project through RESULT|PROJECT page. Users can view the sensitivity analysis result in tabular or graphical format through RESULT|SENSITIVITY ANALYSIS page. Users can also view the production frontier and sediment abatement cost curve in tabular or graphical formats RESULT|ABATEMENT COST CURVE page. Furthermore, users can compare the output from two projects in one table or figure through RESULT|COMPARE PROJECT page.

Map Editor and Browser

The map editor allows users to create new spatial management layers such as fences, water points and ponds in a web-browser. The editor provides current spatial layers as the basic layer and users can add new features to current layers. After finishing editing, the new layer name is prompted from users and the system automatically creates a new shape map that can be used in later analysis.

The map browsers are used to display two types of spatial data: a spatial management layer and result maps. The spatial management layers include the embedded layers and the layers created by users, such as pasture, water point and pond layers. The result map browser displays the outputs of spatial attributes from optimization models on the fly. The types of spatial attributes include upland erosion, grass production, brush production, grass grazed, brush grazed, canopy cover and ground cover predicted from models.

4.3. Database Design and Implementation

The database is the major tool to manage the data in this SDSS. Current database management technologies have a solid theoretical basis and many mature database management systems (DBMS) are available to manage data. This SDSS uses Oracle web database server (9i) as the DBMS. A typical database design and implementation includes requirements analysis, conceptual design, logical design, and implementation. The requirements can be defined by analyzing the application logic. Section 4.1.1 described the database requirement of the SDSS. In the following sections, application logic is first described to understand the major analysis process related with database operation. Then conceptual design, logic design and database implementation are discussed.

4.3.1. Application Logic

Regarding database operation, this SDSS includes two major activities, query and editing data (Figure 4-5). User information management is used in the whole process to identify users and create customized web pages. After login, users can view data through web pages. Users first send a request for data, then the web server queries the database according to the request, the DBMS server queries current database and returns required data to the web server, the web server organizes the data into a formatted web page and returns it to users.

Users can change the data through editing data and running projects. Users first send requests to create or delete data, the web server translates the request into an SQL command and executes the SQL in DBMS. When users send a request to run a project, the web server first queries the database to prepare the required input for a project. After running a project, the web server put the results back to the database. Then the results are available for query.

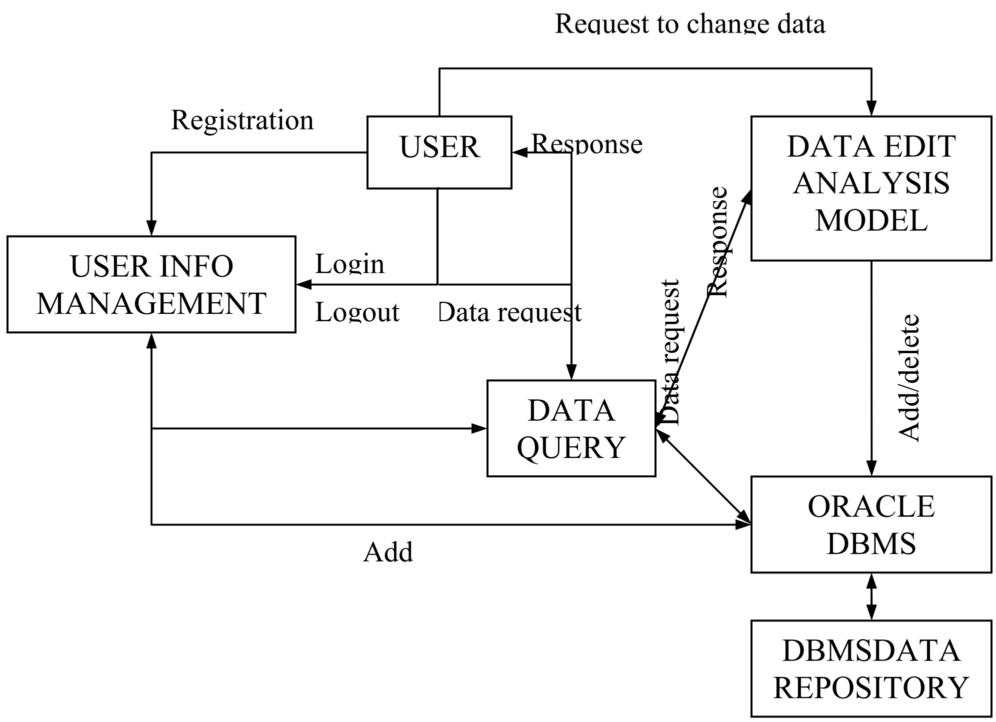


Figure 4-5 Application logic of the SDSS

4.3.2. Conceptual Design

Conceptual design defines the abstract model of data organization. The design depends on the objectives of a database and application logic. The entity relationship diagram, i.e. E-R diagram, is usually used in conceptual design to represent the entities and their relationships. The E-R diagram for this SDSS is shown in Figure 4-7. This database uses a combined primary key in many entities. This design is useful for this type of study. The combined key allows a SQL query to filter the records according to one attribute in a combined primary key without linking different tables, which reduces the table number and the links between tables. Structured query language (SQL) is used to implement the database scheme. The code of the implementation is shown in Appendix B.

4.3.3. Logical Design

Logical design defines the operational relationships among different entities in a database. In this study, the logic to create new data is enforced through explicit validation checks. Before inserting a new record, a SQL query is made to check the format, redundancy and possible conflicts. The deletion logic is implemented explicitly through SQL created by middleware. The deletion is implemented in a cascade pattern. As shown in Figure 4-6, if any data in a box is deleted, all the data that can be reached from that box following arrows is also deleted.

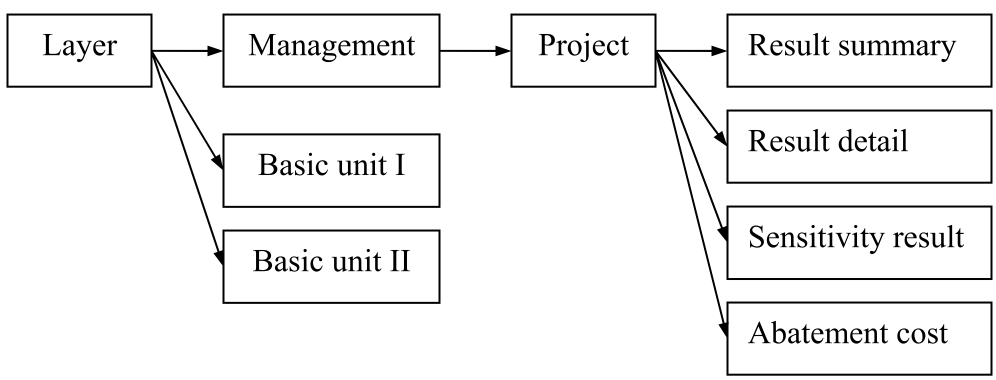


Figure 4-6 Deletion logic in the SDSS database

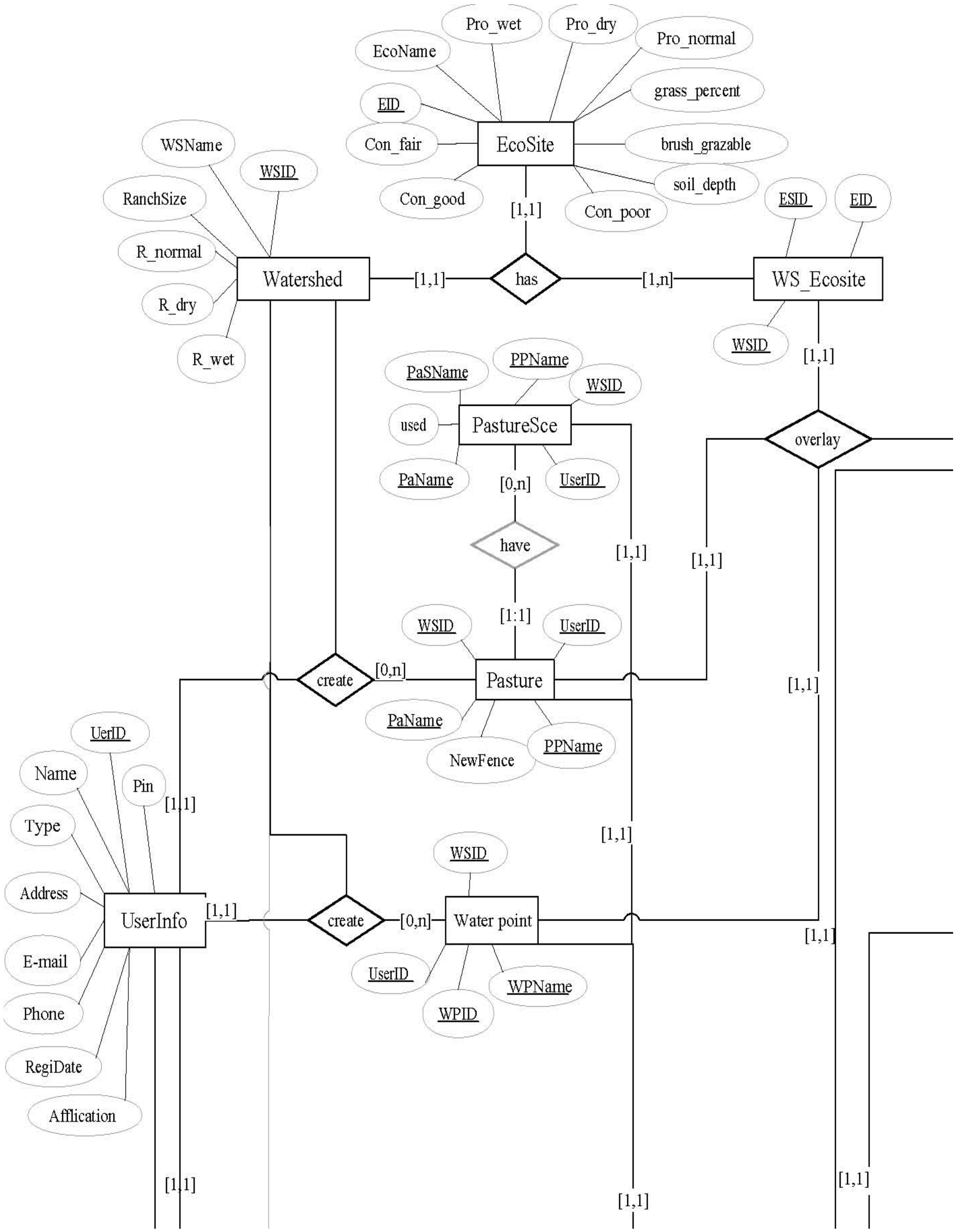


Figure 4-7 E-R diagram. The top left section.

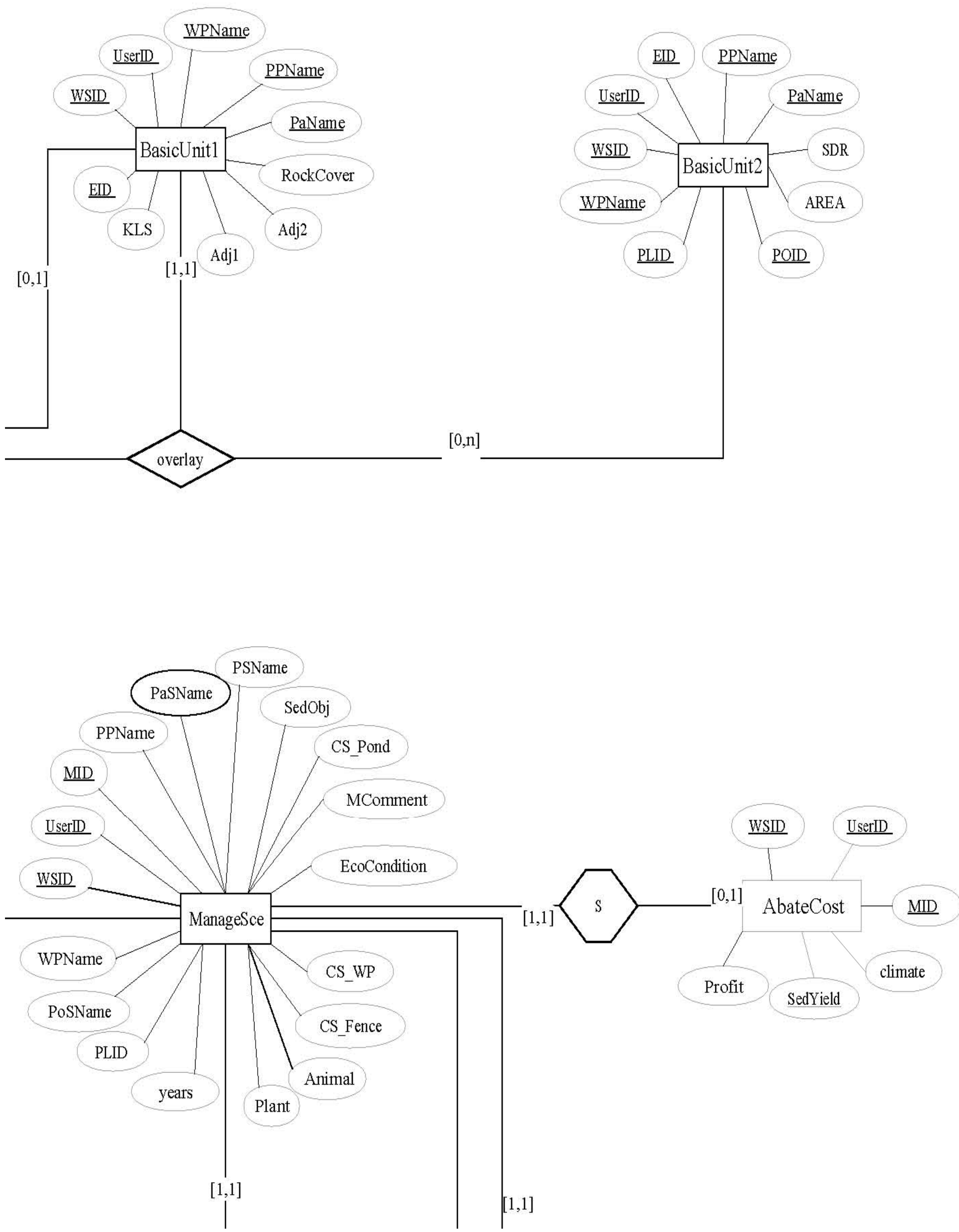


Figure 4-7 E-R diagram – ***Continued***. The top right section.

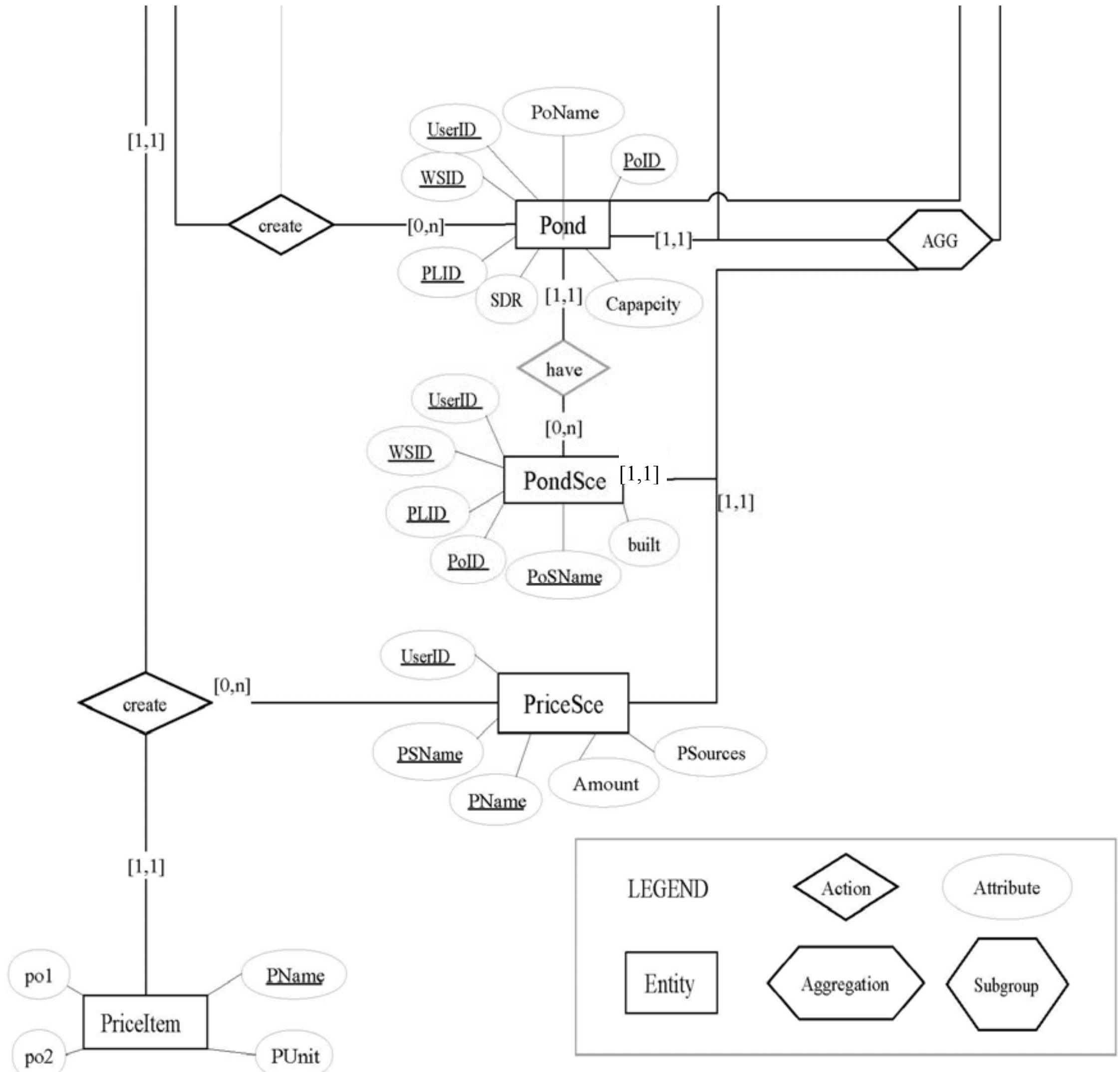


Figure 4-7 E-R diagram – ***Continued.*** The bottom left section**.**

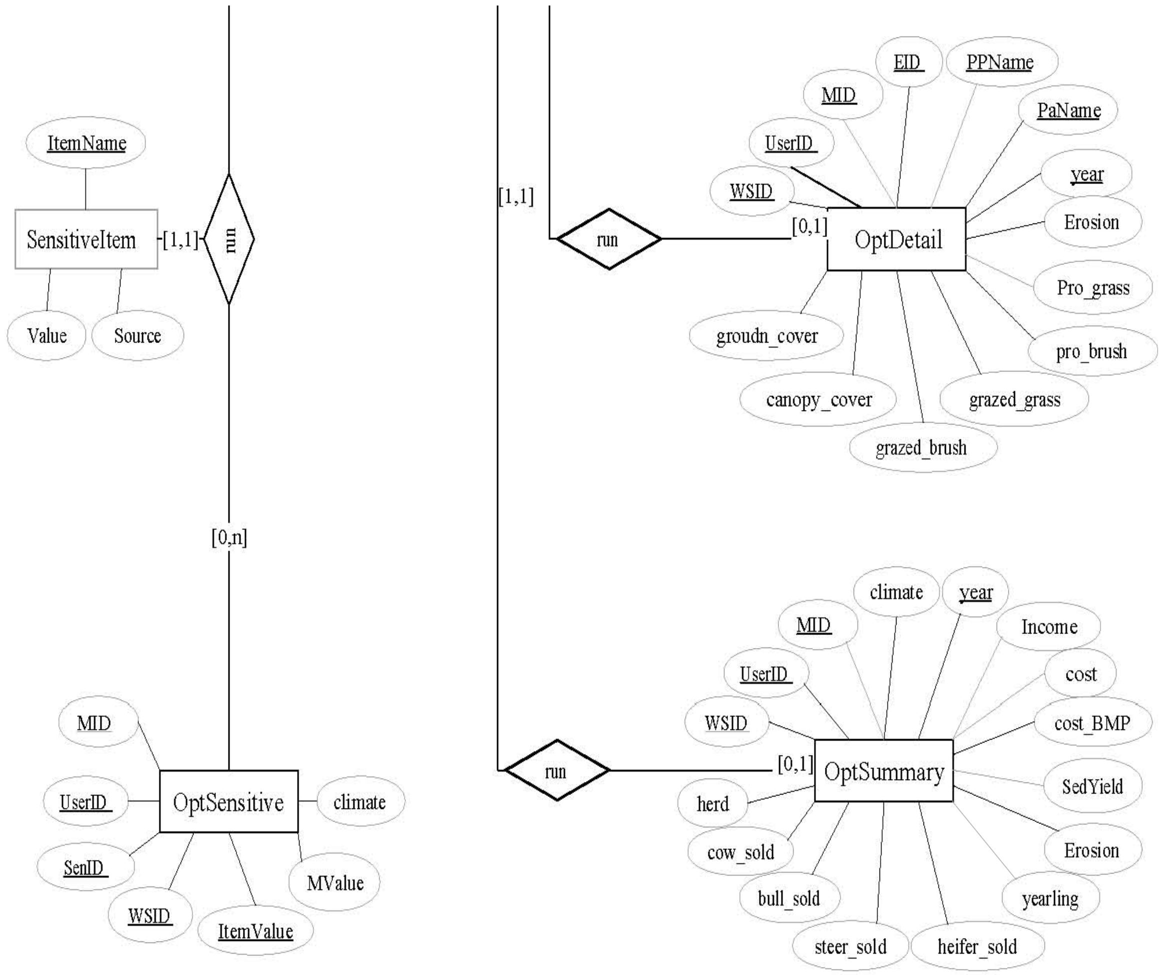


Figure 4-7 E-R diagram – *Continued. T*he bottom right section.

4.3.4. Database Implementation

The database of this study is implemented on the Oracle database server. The database was launched by loading the SQL script in Appendix B into the Oracle Server. The initialization of system data is also loaded into the database through SQL scripts.

4.4. System Integration

The SDSS includes three major parts, the interfaces, database and analysis models. To glue all the parts together in a system, middleware is used to link these parts by providing data communication among them. This SDSS uses several types of middleware.

4.4.1. Servlet: the Backbone of the SDSS

The Servlets are the backbone of the whole SDSS system. The Servlets in the Web server wait for users' requests. Once a request is received, Servlets execute certain actions and respond to the request with corresponding web pages. The actions include communicating with the database, executing GAMS code, making geospatial analysis and redirecting requests to other servers.

4.4.2. Database Integration

The system needs to communicate with the Oracle database intensively to query or manage the data. All the communications with the database are implemented through JDBC technology in Java program, including Servlets.

4.4.3. Geospatial Analysis

MapServer does not support map creation, editing and complex geospatial analysis. A combination of MapServer, AML (ArcInfo Macro Language) and Java middleware are used to meet the geospatial analysis requirements. The geospatial analysis includes creating new layers of fence, water points and ponds, overlaying layers to create basic units and deriving attributes for basic units. The system implements these tasks by calling the corresponding Arc/Info AML. The AML scripts are listed in Appendix B.

4.4.4. Execution of GAMS Model

The optimization models in GAMS code are the major analysis component of this SDSS. GAMS programs require inputs in text format and create an output file in text format. The system uses Java programs that dynamically create input files from the database, start a GAMS program and read the results back to the database in a batch. The creation of the proper GAMS program assembles the parameters of a project from the database and the GAMS code for selected model type in proper format. The models include different plant and livestock types, sensitivity analysis and abatement cost curves.

4.4.5. Help System

The SDSS provides several help methods for users. System documentation web pages are used to provide detailed information of system structure, terminology and analysis of the SDSS. A graphical tutor can be activated to indicate the progress of the analysis. An Email-based help system is also used to provide personal help.

4.5. Use Cases

The above interfaces, combining embedded data and models, provide a platform to analyze economic and sediment impacts of different managements on rangeland watersheds. This section defines use cases to illustrate the procedure of typical applications supported in the SDSS.

4.5.1. Procedure to Implement a Project

Define a Price and Cost Scenario

Users can view the embedded price and cost dataset through the PRICE & COST| VIEW menu. If users have their data, they can input their data to create new datasets. Each price item includes four attributes: item name, unit, value and source. Users can also delete an existing dataset through the PRICE & COST|DELETE menu if they no longer need the dataset.

Edit Spatial Layers

Users can view spatial layers of pastures, water points or stock ponds through a map browser by clicking the EDIT/BROWSER submenu in the PASTURE/WATER

POINT/POND main menu. If users want to create a new layer, they can first go to the map editor page, then follow the procedure listed in Figure 4-8 to create a new layer. Users can also delete existing layers through DELETE pages.

Edit Pasture Layer in the Map Editor

1. Display current fence, click EDIT FENCE button, click ADD button.
2. Click ADD LINE button, then point to starting point and click.
3. Continue adding points by clicking until the end of the new fence, click END LINE button.
4. To add more fences, repeat Step 2 and 3.
5. Click END button, input the new layer name in the popup window, then press ENTER key.

Edit a Water Point/Pond Layer in the Map Editor

1. Display current Water point/pond, click EDIT FENCE/EDIT POND button, click ADD button.
2. Point to new water point/pond and click, repeat this process to add all new points.
3. Click END button, input the new layer name in the popup window, then press ENTER key.

Figure 4-8 Procedure to create spatial layers in the SDSS

Edit Spatial Management Scenarios

Users can define spatial management scenarios of pasture or pond through CREATE page in the PASTURE/POND main menu. Pasture management defines if a pasture is grazed or not in the study period. Pond management defines if a pond is used or not in the study period. Users can also view or delete an existing management scenario through VIEW/DELETE in the PASTURE/POND main menu.

Edit a Project

Users can view, create and delete projects through the web pages in the PROJECT menu. To create a project, users first need to select a pasture layer and pond layer, then specify parameters and input a name for the new project, then the new project is created. Similarly, users can view and delete a project through the VIEW/DELETE page in the PROJECT main menu.

Run a Project

Users can run a project to perform a watershed analysis. Users can simply run a project as a constrained optimization problem. In the RUN PROJECT web page in the RUN main menu, users can select a project and specify climate type, then click the 'RUN" button. If it is a multi-year project, users need to specify a climate type for each year. Then the system automatically executes the proper models of the project.

For one-year projects, users can also run sensitivity analysis and calculate an abatement cost curve/production frontier. To run a sensitivity analysis, users can go to the

RUN SENSITIVITY page; first select a project, a climate type, a sensitivity analysis item, an upper and lower bound of change of each item and a step size for each change, then click 'RUN' button. To run an abatement cost curve/production frontier for a project, users can go to the RUN ABATEMENT COST CURVE page, select a project, a climate type, and then click 'RUN' button. The system automatically activates the corresponding program. After running, the web page is directed to the web page for users to view the results.

View Results

To view results of a project, users can go to the VIEW PROJECT page in the RESULT menu, and then select the project to get the summary data. Then users can view the detailed result by selecting the type that they are interested in. The types of results include economic, sediment and biomass budgets. Economic results present users revenue and cost in a ranch budget table. Forage budgets are summed up according to pastures. Sediment budgets are summed up according to pastures and ponds. Users can also view the spatial distribution of erosion, grass production, brush production, grass grazed, brush grazed, and canopy cover, and ground cover in maps. For multi-year projects, users can view results both in tables and maps for each year by selecting different year.

To view results from sensitivity analysis or abatement cost curve running, users select the SENSITIVITY page in the RESULT menu, then select project name, the sensitivity analysis or abatement cost curve will be displayed both in graphic and tabular format. For each abatement cost curve, there is a corresponding production frontier. The production frontier can be displayed by clicking the ‘GET PRODUCTION FRONTIER’ button just below the abatement cost curve figure.

4.5.2. More Complicated Applications

The previous section describes the procedure for a single project. A practical application may require more complicated analysis for different managements to support the best management practice options. The complicated application is intended to provide more results in a batch process.

Sensitivity Analysis

Sensitivity analysis can be made through two approaches in this SDSS. The first approach is to use the SENSITIVITY web page in the RUN menu, just as described in the previous section. This method can only change one item each time. The first approach is simple to implement. The second approach is to create different projects. By setting the proper value for the items in different projects, users can compare the results manually to finish the sensitivity results. Although the second approach provides flexibility in sensitive analysis, it also requires more steps to implement in the SDSS.

Compare Management Alternatives

Results from current ecological and erosion models have high variance. The high uncertainty requires more robust methods to evaluate the results. The production frontier provides a robust method to rank two management alternatives. If a project can give high rank on all sediment control levels and at any climate, the management alternative should have a higher rank.

Users can compare results of two projects through the COMPARE page in the RESULT main menu. Users can compare the summary data by listing them in a table to highlight differences. The SDSS can also put two production frontiers in one figure. Then users can compare the range of possible sediment yields for each project and the profit associated with each sediment yield level. This is useful to rank two different management options.

4.6. Extension

The SDSS provides the routine procedures to extend the SDSS for more applications. This study allows two types of extensions. The first is to add a new watershed to the system. The second is to add new model options to the system.

4.6.1. Add Watersheds

Corresponding to the discussion in Section 3.10.2, adding a watershed could be easy or difficult. Three types of watershed extensions are discussed here. The first type is to add a new watershed that is a sub-watershed of the current watershed. Three steps are needed to implement this extension.

1) Get the boundary layer of the new watershed and implement the processes in Figure 4-2, this can be automatically done by running an AML.

2) Input the basic information of the new watershed into the database.

3) Change the web page to include the new watershed.

The second type is to add a new watershed located in the same climate zone as the current watersheds. The process is similar to the first case. But more data are required to be collected to make the extra spatial analysis. The spatial layers required include a DEM, soil maps, ecological maps and fence lines, water points and stock ponds. The preprocessing of these layers is shown in Figure 4-9. The database input requires the new ecological site information. If a new ecological site appears, the ecological data table also needed to be updated with the data of that ecological site.

The third type is that new watersheds that may be significantly different from current watersheds in climate or vegetation. This type of extension may require new model types for their special biophysical processes. This extension is generally more complex and may require rewriting the code.

4.6.2. Add New Models

Adding a new model to the SDSS corresponds to the function extension in Section 3.10.3. Generally, adding a new function to the current system is complex. The extension needs to consider if the new model is compatible with current data structure, Servlet and web page . In most cases, the extension requires creating new model in GAMS code, to change database structure and interfaces.

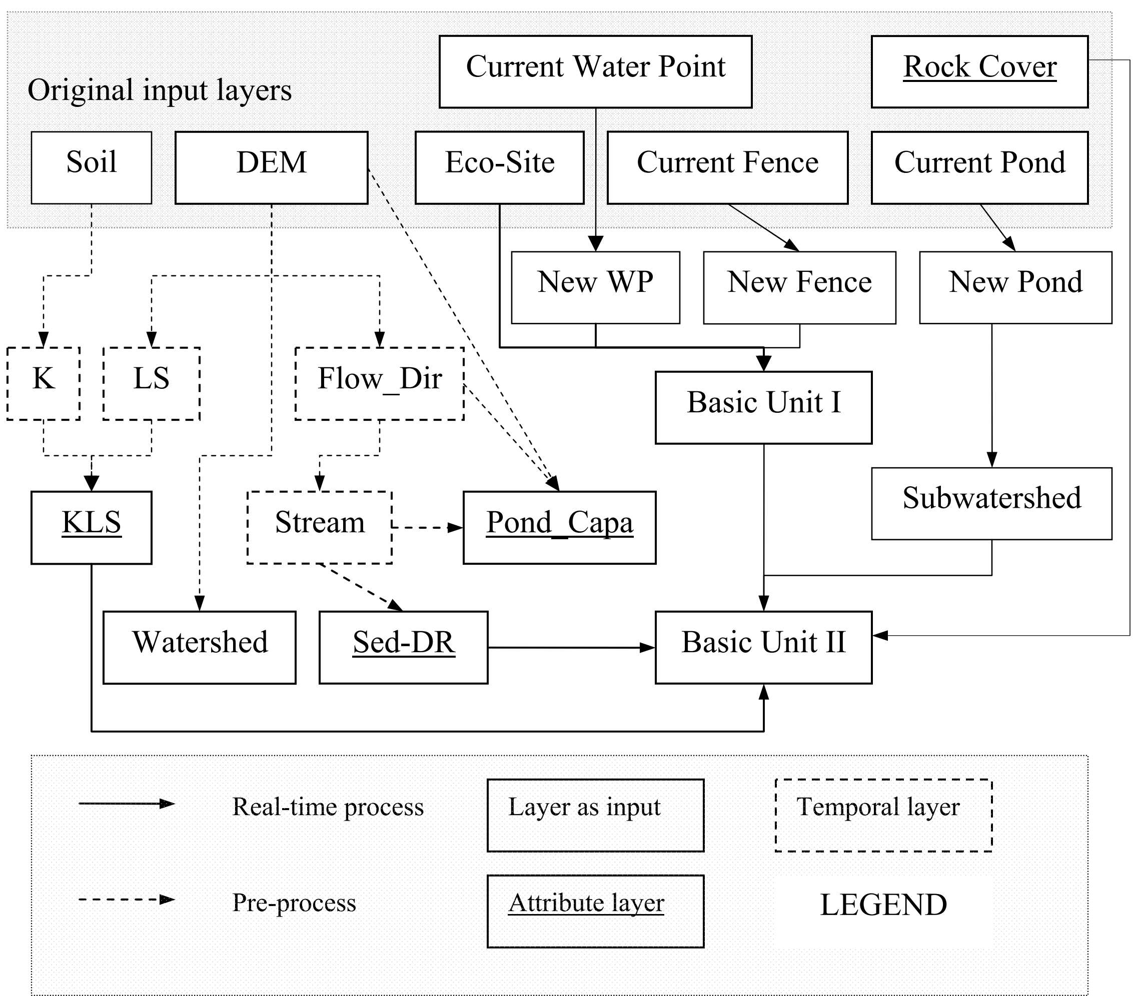


Figure 4-9 Data layers and geo-processing in the SDSS

4.7. Summary

This chapter describes the architecture, interface, database and system integration of the SDSS. This SDSS uses hybrid techniques to provide web-based interfaces that could efficiently manage the users' data and provide a flexible interface to aid users to make analysis and present analysis results. This centralized data management mode provides an efficient way to distributed information for decision making and a web-based integrated system provides the wide access for users with the least requirements for hardware and software. In the next chapter, a case study of the Walnut Gulch Watershed is developed to demonstrate the functionality of this SDSS.

CHAPTER 5 CASE STUDY: WALNUT GULCH EXPERIMENTAL WATERSHED

5.1. Introduction

The Walnut Gulch Experimental Watershed (WGEW) is located in southeastern Arizona, USA. (31^{o}43'N, 110^{o}41'W). The watershed is a subwatershed of the Upper San Pedro River Basin (Figure 5-1). The total watershed area is about 149 square kilometers. Two major vegetation communities dominate the watershed, with grassland on the eastern upstream area, brush on western low-elevation area and small portions of woodland on the northeast corner. Cattle grazing is the primary land use, about 90% of the total area. The other land uses includes urban area, mining, and roads. USDA/SWRC has managed the experiment watershed for past five decades and accumulated lots of data and research literature. A summary of the major information about the Walnut Gulch Watershed can be found in the brochure (SWRC, 2003).

Sediment control is important to maintain the water quality of the San Pedro River. The riparian system of the upper San Pedro River has a critical role in the regional ecological system (Figure 5-1). Thus, the San Pedro National Conservation area (SPRNCA) was set up in the riparian area to protect the riparian ecosystem. The increase of human activity in this area requires better management to coordinate humans' activities and environmental conservation. The EPA water quality report (EPA, 2004). showed that turbidity, mainly from sediment, was a major pollutant that puts part of the stream on the 303D list and thus required a TMDL for the area. The increased sediment concentration in water may damage the ecosystem in the conservation area.

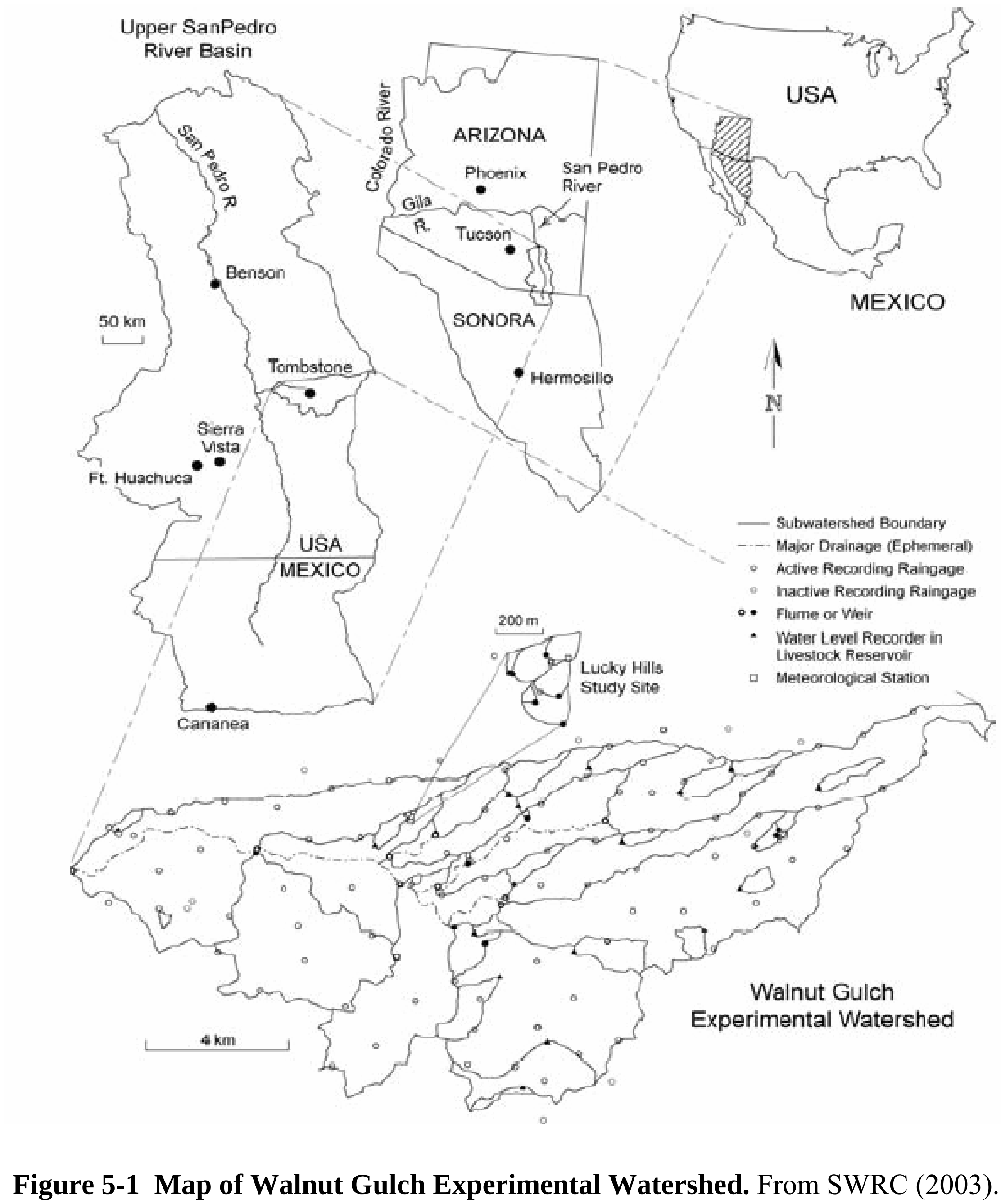


Figure 5-1 Map of Walnut Gulch Experimental Watershed. From SWRC (2003).

As a branch of the Upper San Pedro River, the Walnut Gulch Watershed contributes sediment loads to the San Pedro River during the summer monsoon season. Reducing sediment yield from the watershed will improve downstream water quality. This case study makes a prototype study of controlling sediment yield of this watershed from an economic perspective. The SDSS is useful in assessing the sediment control plan and the results may be used in design of the TMDL plan that can protect San Pedro River Ecosystem.

5.2. Parameterization

Parameterization is required before launching the SDSS for the Walnut Gulch Watershed. The general procedure of SDSS parameterization was described in Chapter 3 and 4. This section describes the detailed parameterization of the SDSS of the Walnut Gulch Watershed.

5.2.1. Geospatial Layers and Preprocessing

The geo-processing in this SDSS requires spatial inputs, including a digital elevation map (DEM), soil map, ecological site map, and current infrastructure maps of fences, ponds and water points. The DEM (10-meter resolution), soil map, ecological site map, current pond map in this SDSS were from the ARS/SWRC spatial data server. The fence map and water point map were created from field investigation. The watershed boundary is considered as the border the representative ranch and artificial water points were added to provide adequate water for pastures having water points out of the watershed. The map of current fences, water points and ponds are shown in Figure 5-2. The ecological site map is showed in Figure D-1. The ecological properties are shown in Table C-2.

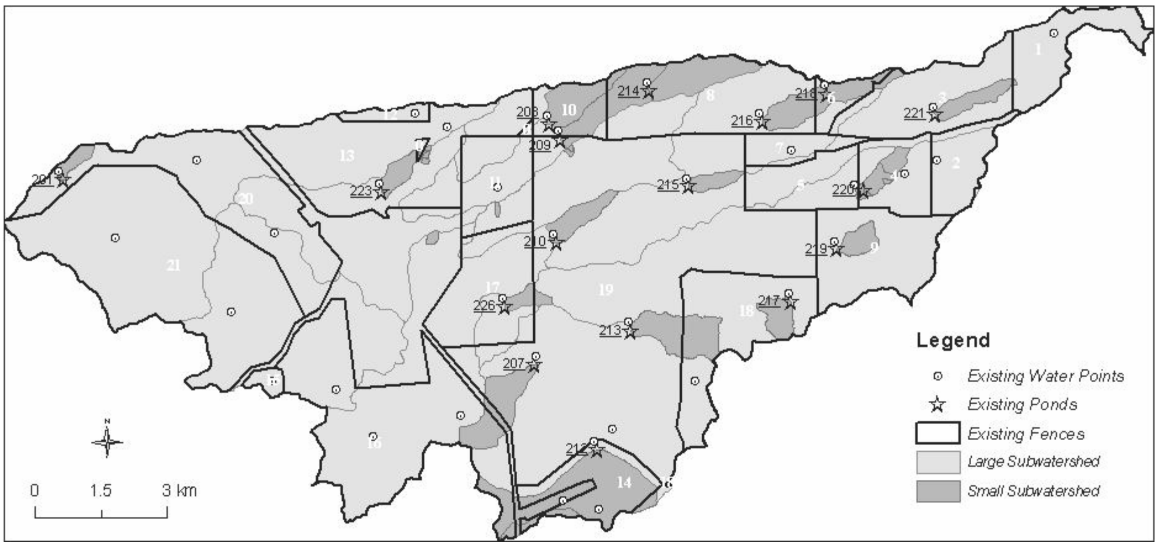


Figure 5-2 Current fences, ponds and water points in the Walnut Gulch Watershed

Before launching the SDSS application, geospatial preprocessing (the dashed arrows in Figure 4-9) was executed to generate the layers that are needed in web-based analysis. Most geo-processing was performed on the DEM or its derivative layers. The watershed boundary, flow direction, channel system, pond capacity, LS factor and rock cover were created directly or indirectly from a DEM using ARC/INFO commands. The delineation of the watershed boundary and calculation of flow direction are standard commands in ARC/INFO. The stream networks were defined as the cells that have the accumulated flow area over 5 hectares. The stream network from the process roughly matches the stream channel system from the survey map with some minor differences in the small channels (Figure D-2). The pond capacity layer was estimated by computing the pond volume with one-meter effective dam height from the DEM. The RUSLE topographic factors, L and S, were calculated by running the AML from Hikey (2003). The rock cover map was derived using the relationship of Simanton et al. (1994). The soil map was converted into a RUSLE K map using a lookup table (Table C-3). Then the K-factor map and LS map are multiplied to create the KLS map.

The sediment delivery ratio (SDR) map is an input to compute sediment yield. This case study used the following method to derive the SDR map. The whole watershed was divided into channel cells and slope cells. For each slope cell, a delivery ratio between two adjacent cells was assigned according to the following relationship:

$$\mathrm{DR} = \begin{cases} 1 & \mathrm{S_{UP}} \le \mathrm{S_0} \\ 1 + 0.327\ln(\mathrm{S_{UP}} / \mathrm{S_0}) & \mathrm{S_{UP}} > \mathrm{S_0} \end{cases} \qquad (5\text{-}1)$$

where S_0 is the slope of a focus cell, S_{UP} is the slope of the adjacent upstream cell. This relationship was derived from the RUSLE2 simulation of a two-segment slope with the typical soil type and vegetation of the Walnut Gulch Watershed (Figure 5-2). By changing the slope combinations of two segments, sediment delivery ratios are computed. The delivery ratios were regressed to the slope ratios for all cases with the slope ratio, $S_{UP} / S_0 < 1$.

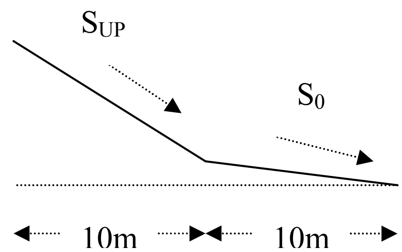


Figure 5-3 Slope profile in the RUSLE2 simulation

For channel cells, a constant DR was assigned to all cells. The constant was selected to make the overall SDR of whole watershed approximate the estimation of sediment yields, i.e. 0.41, by Lane et al. (1997) After all cells have the local DR, then the SDR for each cell from that cell to the outlet was derived by multiplying the DR along the flow path from that cell to the outlets. The derived SDR map is shown in Figure D-3.

5.2.2. Price and Cost Data

The price and cost data are mainly from Teegerstrom and Tronstad (2000). The data are for the ranches of the Southeastern Arizona. The values of the default dataset are listed in Table C-1. The values for these costs per cow are from Teegerstrom and Tronstad (2000).

5.3. Validation

Model validation is important in model development. There are different validation methods (Balci, 1996). The selection of validation method depends on the available observation data, model type and study objectives. In practice, one or several methods may be used in model validation.

The validation in this study was done through comparing the observed data and the model results under current conditions. Because detailed data about ranch management in Walnut Gulch Watershed is not available, as well as vegetation and sediment yield of the watershed for recent decades, it is impossible to compare observed data with model results. Currently available observed data are from various sources and are derived under different conditions. The predicted results are derived from the model under current management infrastructure, fair ecological condition, normal climate and no sediment yield constraints. The detailed predicted results under current conditions can be found in Section 5.4.1.

The spatial distribution of vegetation from model prediction was compared with the observed data. The vegetation types from the model prediction (Figure 5-7) roughly match the distribution of the grasslands and brush lands (Renard, 1970). Qi et al. (1993) estimated the mesquite and evergreen covers for the San Pedro River Basin from remote sensing images. These two covers are averaged over each basic unit. The average canopy cover from remote sensing is about 5.3% and the model simulation is about 6.9%. The simulated covers and the observed covers from the remote sensing are plotted against the area (Figure 5-4). For most basic units, the SDSS simulated covers are higher than the values from remote sensing while the covers from remote sensing have a larger range.

This discrepancy implies that the natural vegetation has higher spatial heterogeneity than model simulation.

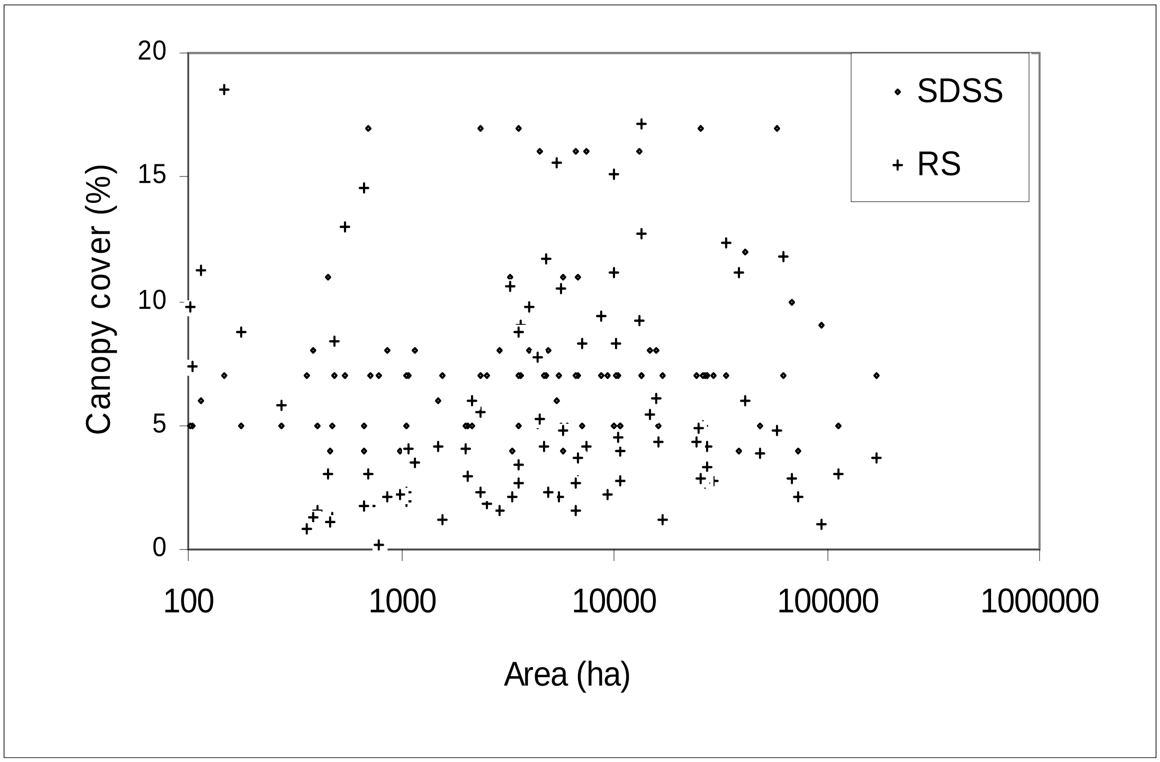


Figure 5-4 Comparison of the canopy cover in each basic unit from the SDSS prediction and the remote sensing (RS) estimation

The predicted ranch management results are compared with the results from another method in southeastern Arizona. The total stocking rate predicted by the model is 276 cow/calf pairs that the grazing lands in the watershed can sustain. The number approximates to the number, 300 cow/calf pairs, based on the initial stocking rate of ecological site description report. The actual stocking rate may be a little higher than the estimated value because some ecological sites have better ecological condition than the assumed fair condition.

The predicted total sediment yield at Flume 1 is compared with the results from other studies. The model predicted the total erosion was about 16 thousands U.S. tons/year on the grazing land and the sediment yield about 5 thousands U.S. tons/year. According to the measured data at Flume 1 during 1957-2003, which measures the total runoff of the watershed, the annual mean runoff is 3.17 mm flow depth across the watershed and the annual median runoff is 1.96 mm. If the sediment concentration varied from 1 to 3% (Lane et al. 1997), the range of the annual sediment yield is about 5170 to 15510 U.S. tons/year for the mean runoff depth and is about 3190 to 9570 US tons/year for the median runoff depth. Another method to estimate the total sediment yield is to use a sediment rating curve. Renard (1969) derived a sediment rating curve for Flume 1. The relationship is applied to all the runoff data of Flume from 1957 to 2003. This method gave an annual suspended sediment yield is of 3534 tons per year. Lane et al. (1997) reported the sediment yield is about 26551 tons per year, which is based on the data in 1960's, the wettest decade of the observed record. Because each method is based on its own assumptions, the sediment yield predicted varies widely. However, the predicted sediment yield from the model is in the reasonable range.

The spatial distribution of predicted erosion and sediment yield in Walnut Gulch Watershed was also compared with the results from other approaches. Nichols (2005) measured the sediment yield for eight small pond watersheds. Lane et al. (1997) summarized a series of sediment yields of plot, small watershed and the whole watershed from several previous studies, which were based on the 1960's data. The results from the two studies are called Nichols' and Lane's series in following paragraph.

AGWA/SWAT (Burns et al., 2004) was also used to derive the distribution of sediment yield. AGWA is a GIS interface to run an embedded SWAT model. SWAT is a distributed watershed hydrological model to simulate long-term runoff and erosion. The details of input and output for AGWA/SWAT simulation are described in Appendix F. The outputs from SWAT are compared with observation data (Table F-1 and Figure F-1). The results show that the simulated runoff at Flume 1 is higher than the observed runoff and the sediment yield is higher than available results. Worthy of note, the upland erosion from the SDSS and SWAT simulations are very close (Table F-1). From the SWAT simulation, the sediment yield of the watershed is much higher than the total upland erosion, which implies that a significant portion of sediment yield is from channel erosion that is not counted in SDSS models.

Because the spatial scale is an important factor in controlling sediment yield (Lane et al. 1997), the sediment yield results from different methods are plotted against the watershed area (Figure 5-5). The sediment yields varied with different approaches and spatial scale. The trends show that Lane’s series has the highest values, and Nichols’ is a little lower. One reason for the difference is that Nichols’ data included the recent period with the low precipitation. The results from SDSS are generally lower than Nichols’ and Lane’s. The SDSS prediction ignored gully and channel erosion, so the difference for the area with high runoff generation is larger than that in the area with low runoff generation area. The results for low runoff areas, such as Pond 201, 207 and 213 matches Nichols’ data well while the model significantly underestimated the high runoff area, such as ponds 214, 215, 216 and 223. SWAT simulation shows the high variance in the erosion, many units have no erosion and some units have very high erosion.

The validation of the SDSS is incomplete. The available data about spatial distribution are limited and are from different sources. The settings of model simulation and observation are also different. Furthermore, the SDSS model was developed on several assumptions that may increase errors is model prediction if the assumptions are not met. Further validation should be performed for a better simulation in the SDSS when additional sediment data become available.

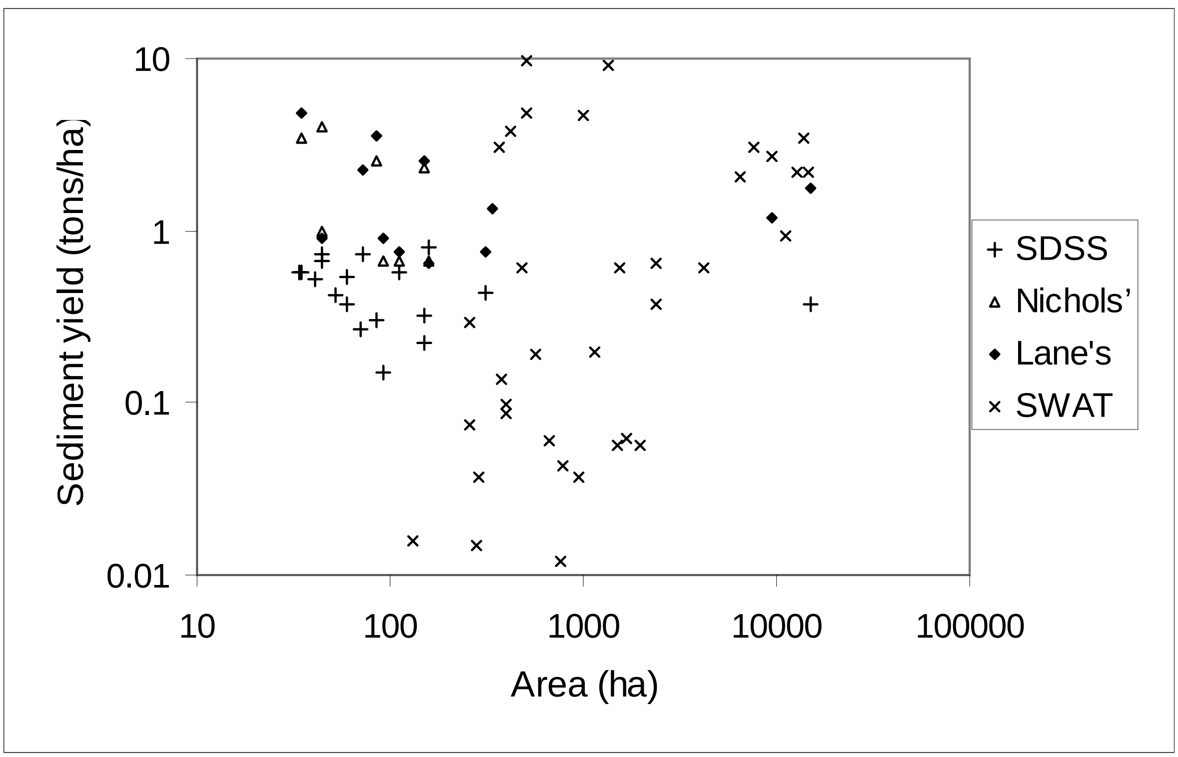


Figure 5-5 Comparison of the sediment yields from different studies

5.4. Sample Applications

This section defines eight sample applications to illustrate the typical analysis that the SDSS can perform on sediment control in a rangeland watershed. The first application shows the details of the predicted results under current conditions and management. It also shows the impacts of different model and climate types. The second application demonstrates the economic and environmental impacts of reducing sediment yield through grazing intensity management. The third application demonstrates the impacts of adding new water points. The fourth application demonstrates the impacts of adding new stock ponds. The fifth application demonstrates how the SDSS might be used to assess ecological condition improvement projects. The sixth application demonstrates the assessment of the effectiveness of cost sharing policy. The seventh application demonstrates the comparison of different management combinations. The eighth application demonstrated how the SDSS might aid in deriving adaptive managements for climate fluctuation using the dynamic model

Each application is organized into three parts: the study objective, the implementation procedure in SDSS and the analysis of results. For simplicity, each example only includes a few changes of current conditions. A practical TMDL in a watershed may include more control measures than these examples.

5.4.1. Application 1: Current Condition Simulation

Objective

The current status is the basis for all other analysis. Current observed data are the results of current conditions. If a project uses current conditions as inputs, the predicted results should approximate the observed data, as the first step in model validation. The current status is also the reference to compare all other management and policy options. Besides providing the results for the validation in section 5.3, this application shows more detailed prediction results. The results include the spatial distribution of forage production, grazing intensity, biomass states and erosion, and ranch economics. The application also shows how different model types and climate may affect the prediction.

Procedure

The first step is to create several new projects in PROJECT|CREATE. The settings are based on the current conditions: default ranch infrastructure of fences, water points and ponds, the default management scenarios of the pastures and ponds, fair ecological condition, normal climate, no binding sediment control constraint, one year planning period, constant plant production and Range Map grazing type. The map of current water points, fences and ponds is shown in Figure 5-2. To compare the different model types, three new projects are created by selecting different model type combinations. To compare the impact of climate, two projects are created with dry and wet climate types respectively. Then each project is run in RUN|PROJECT and RUN|ABATEMENT COST CURVE. After running, view the results.

Results

The model predicts a stocking rate of 276 cow/calf pairs. The sediment yield is about 5030 tons /year. The comparisons in Section 5.3 show that the total stocking rate, sediment yield and vegetation reasonably matches the observed values.

The model also predicts the spatial distribution of major factors. The erosion rate varies significantly across the watershed. The most eroded areas include the areas of the northwestern and southeastern watershed and mountain areas (Figure 5-6). The grass-dominated areas usually have lower erosion rates than those in the brush-dominated areas. The sediment budget summarized over each pasture and pond is listed in Tables E-3 and E-4.

Forage production distribution shows the two major vegetation areas (Figure 5-7 and 5-8). The grasslands located on the eastern uplands have high grass production, high ground cover and low erosion rate (Figure 5-6 and 5-7). The brush lands are located on the western low-elevation area and cover two thirds of the total watershed area. The brush lands have high brush production, low grass production, low ground cover and high erosion rates (Figure 5-6 and 5-8). The carrying capacity of these two vegetation types are different (Figure 5-7 and 5-8) and the major source of forage is from the grasslands.

The difference is more obvious from the summary of carrying capacity of different pastures (Table E-2).

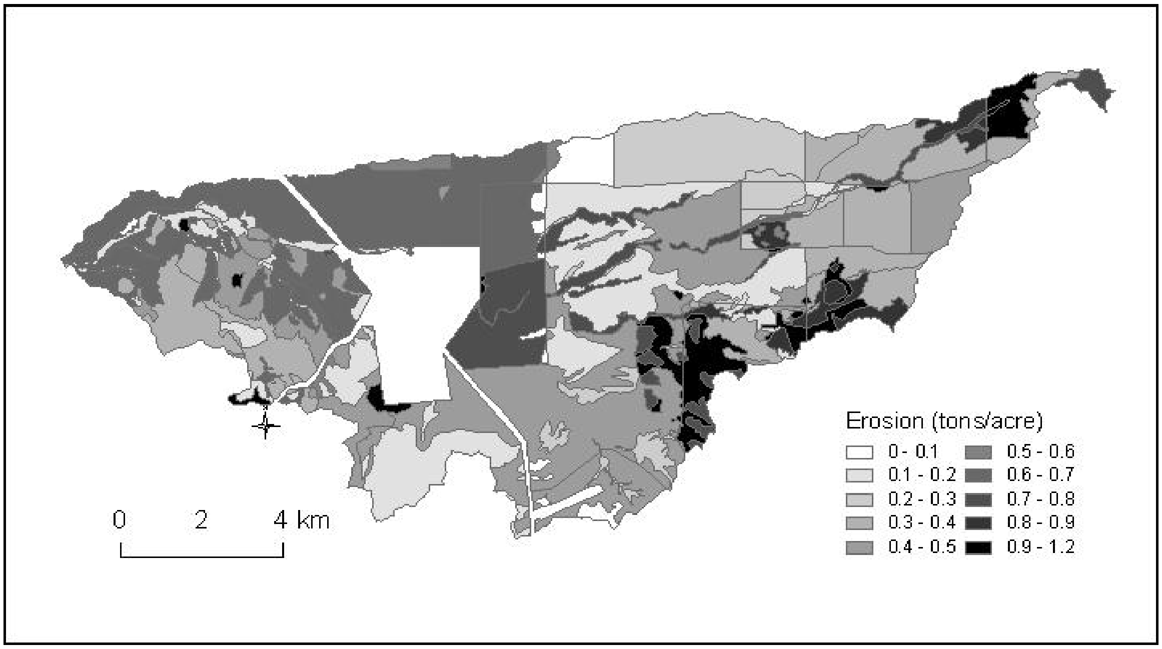


Figure 5-6 Map of the erosion map of the default project with current infrastructure, under fair condition and normal climate

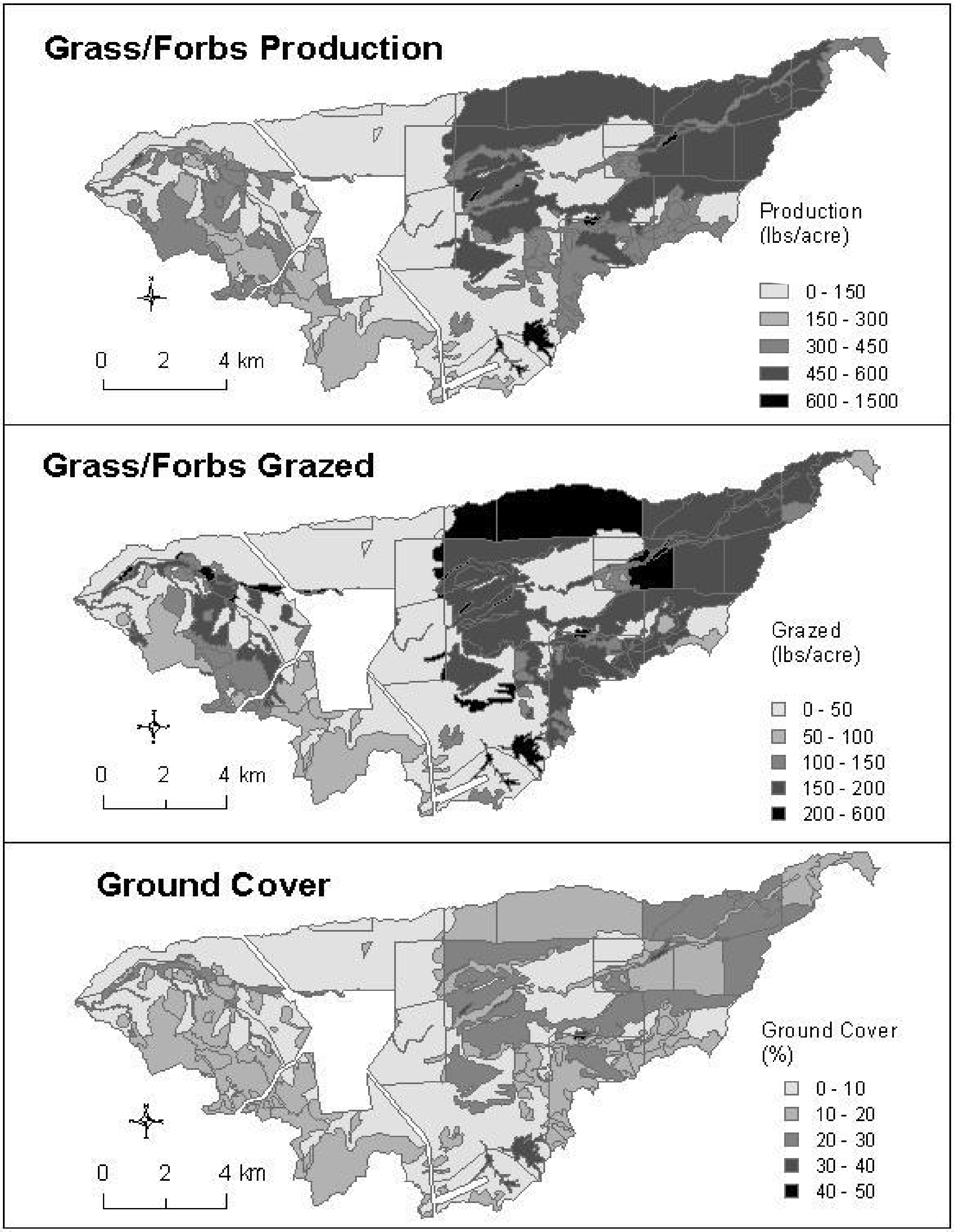


Figure 5-7 Map of the grass/forbs production, grazing and ground cover of the default project with current infrastructure, under fair condition and normal climate

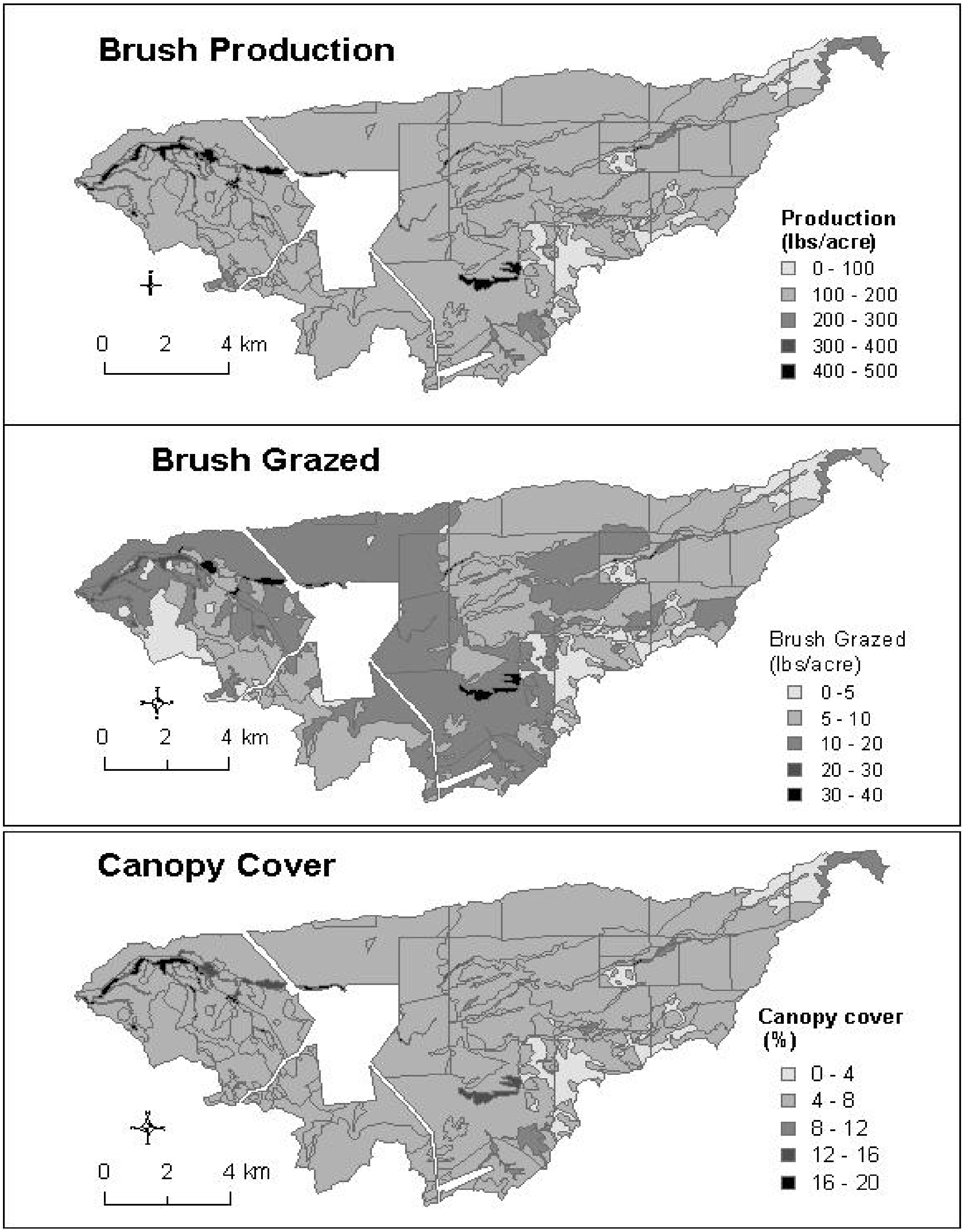


Figure 5-8 Map of the brush production, grazing and canopy cover of the default project with current infrastructure and under fair condition and normal climate

The SDSS supports four model options. The four model options are four combinations of two grass production types and two grazing types. Different types create slightly different results. For example, in Figure 5-9, the production frontiers of different models show different output ranges and conversion ratio. The results show that the model with inverted 'U' plant growth curve gives a higher estimation of carrying capacity than that with the constant growth curve. The production frontiers also show that the model with Range Map grazing type gives a lower prediction of carrying capacity than that with regression grazing type. The abatement cost curve is similar at small sediment reductions (Figure 5-9).

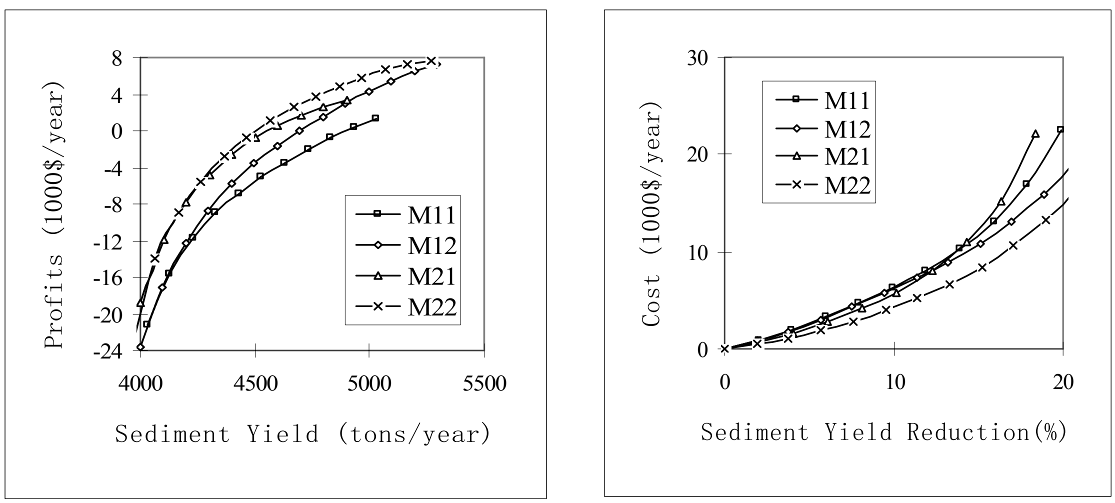


Figure 5-9 Production frontiers (left) and abatement cost curves (right) of the default project with different model types. The first number in the legend indicates the plant type and the second number indicates the grazing type. Plant type: 1 no grazing impact, 2 inverted 'U' relationships; grazing type: 1, Range map, 2 regression equation.

Climate types can significantly affect the carrying capacity and erosion rate of rangeland. The production frontiers (Figure 5-10) show that wet climate dominates normal climate and normal climate dominates dry climate in both carrying capacity and sediment yield. The high production in a wet climate provides flexibility in erosion control by controlling grazing. Higher runoff with a wet climate may increase the total sediment yield. Dry climate can put great pressures on ranch production and erosion control. This impact is shown more clearly in the results from the dynamic models in Section 5.4.8.

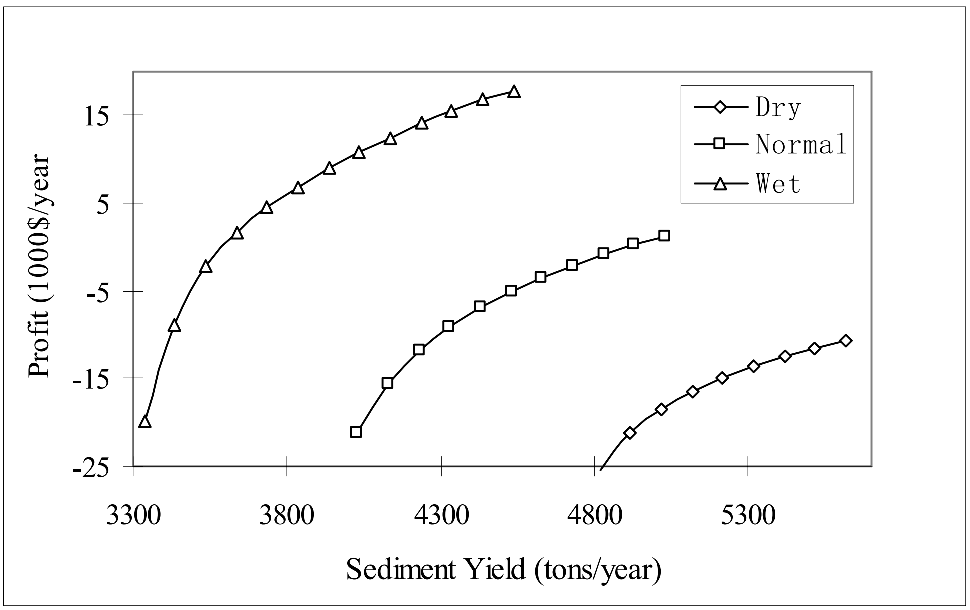


Figure 5-10 Production frontiers of the default under different climates

5.4.2. Application 2: Reducing Sediment Yield through Grazing Management

Objective

Grazing management is a short-term management tool to control forage utilization. In practice, ranchers adjust stocking rates to adapt to forage supply. It is critical to keep a proper stocking rate for different pastures in a ranch. Because stocking rate not only affects the vegetation condition and consequently affects sediment yield, stocking rate is a tool to control sediment yield. This application illustrates how the SDSS adjusts stocking rates with different sediment objectives, what the economic impacts of the adjustment are, and how the spatial distributions of stocking rate changes with the sediment control objective.

Procedure

The settings for the project are the same as the current condition project in Section 5.4.1. First run the RUN|ABATEMENT COST CURVE to get the abatement cost curve. Then create new projects with sediment yield reduction of 250, 500 and 750 tons/year, corresponding to about 5%, 10% and 15% of sediment yield reductions. Run the model in the RUN|ABATEMENT COST CURVE and view the results.

Results

The marginal cost of sediment yield control increases with control objectives. The abatement cost curve looks like a convex function (left part in Figure 5-11). The marginal cost curve is derived from the abatement cost curve (right part in Figure 5-11). The initial sediment reduction is less costly, and the cost increases rapidly after the sediment yield reduction is more than 10% of sediment yield. If all grazing is phased out, the sediment yield cannot be reduced through additional grazing management. So grazing intensity control may be a cost effective alternative in sediment control only up to a certain level.

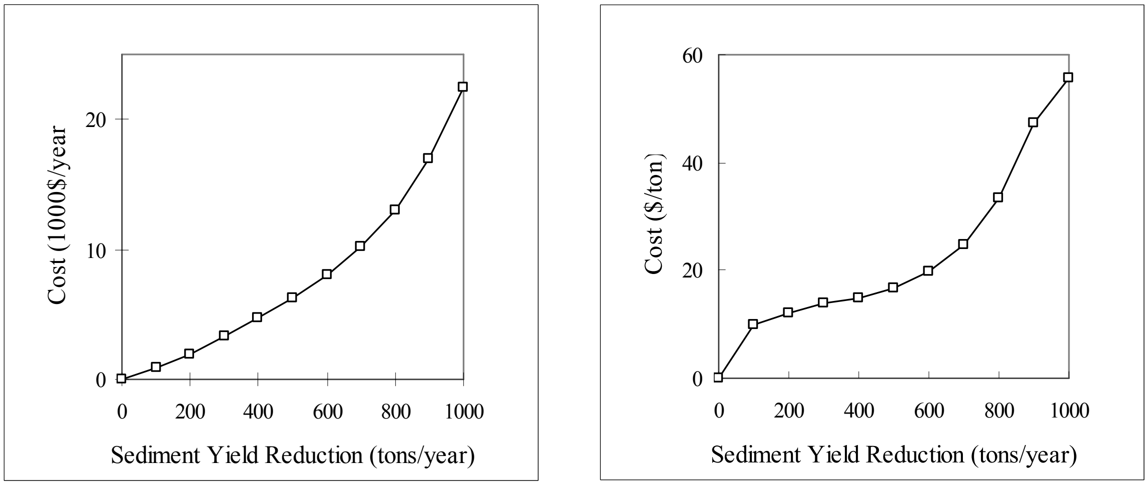


Figure 5-11 Abatement cost curve and marginal cost curve with current infrastructure and under current ecological condition and normal climate.

The spatial pattern of grazing intensity adjustment shifts from downstream to upstream with increasing sediment control reduction (Figure 5-12). The adjustments mainly occur near the outlet for the low sediment control objective, and then the adjustments move further from the outlet with more sediment yield reduction. The erosion rates also change spatially with the grazing adjustment (Figure 5-13). This change is reasonable because the area near the outlet has a high sediment delivery ratio and one unit of erosion reduction can reduce more sediment yield than that of an area further from outlet.

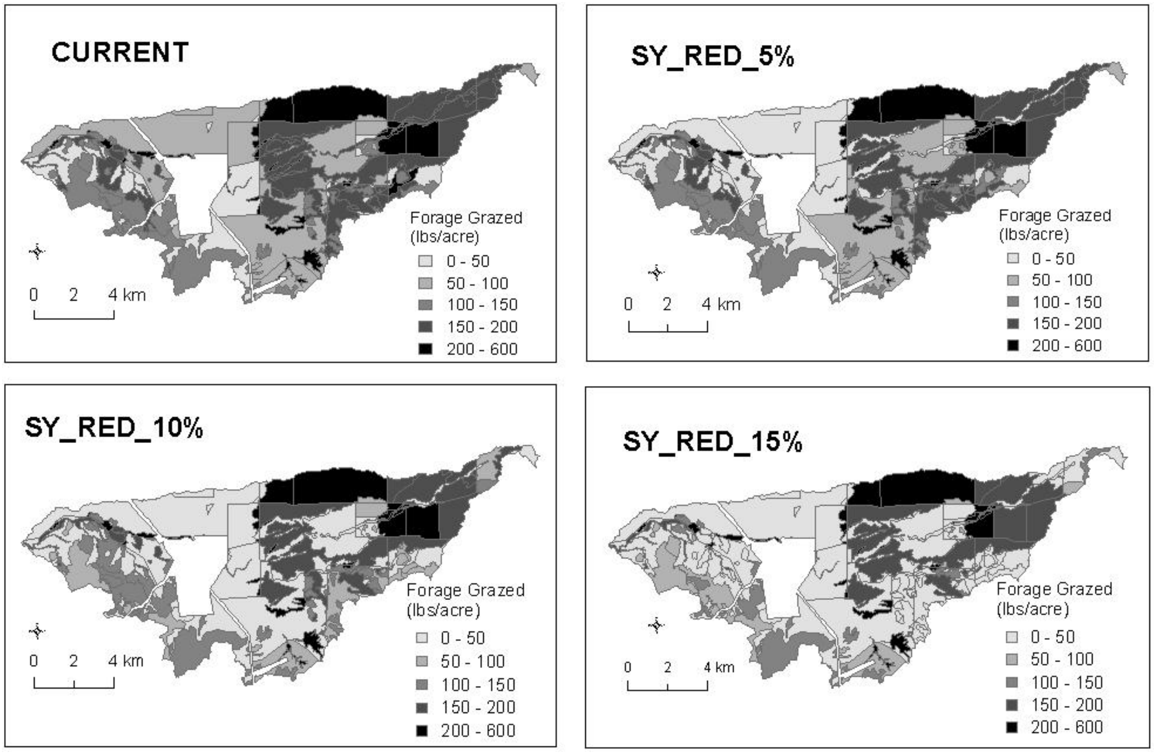


Figure 5-12 Spatial adjustment of grazing with different sediment control objective

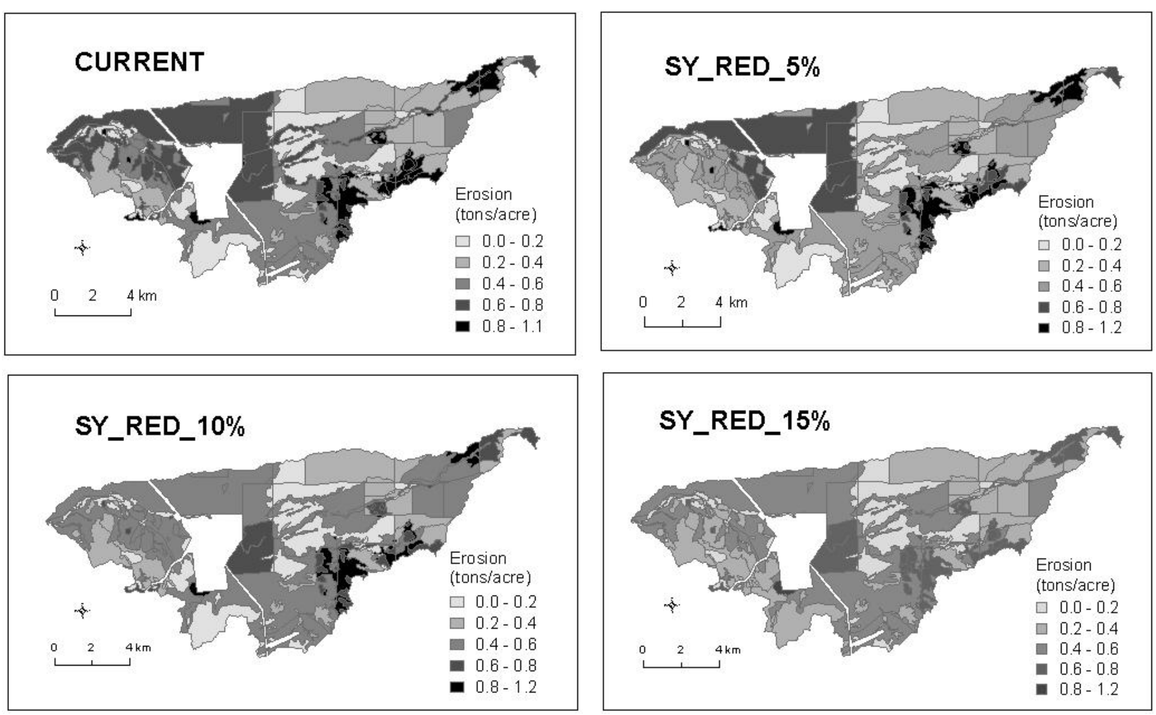


Figure 5-13 Upland erosion change with different sediment control objective

From another perspective, the stocking rates of different pastures are adjusted in different proportions (Figure 5-14). The stocking rates in the pastures near the outlet are reduced more rapidly at the low sediment reduction. For the initial 10% sediment yield reduction, the reduction in most pastures is not very significant. However, more reduction in the sediment yield greatly reduces the stocking rate and the ranch revenues. The information is useful in guiding ranchers to adopt proper grazing intensity to efficiently reduce sediment yield.

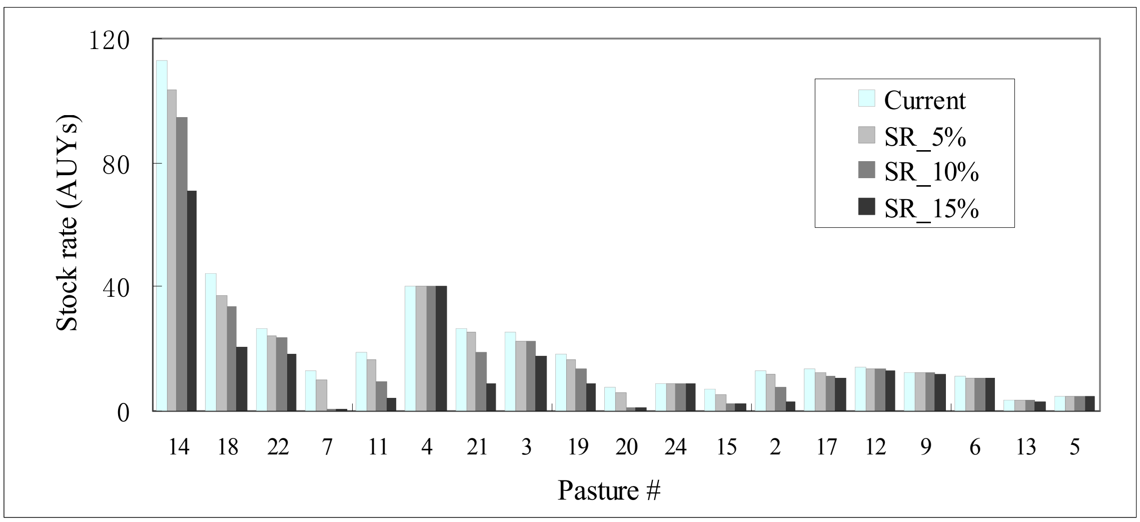


Figure 5-14 Stocking rate adjustment in the pastures for different sediment yield reductions

5.4.3. Application 3: Reducing Sediment Yield by Adding Water Points

Objective

Water points are infrastructure to control grazing distribution. A water point is a long-term management tool. Adding water points allows ranchers more sophisticated control of grazing distribution, which may increase carrying capacity and reduce overgrazing. However, new infrastructure increases construction and maintenance cost. This application illustrates the impacts on ranch income and sediment yield of adding new water points.

Procedure

Create two new maps with new water points on grassland and brush land respectively, the locations are shown as Grass_WP_1 and Brush_WP_1 shown in Figure 5-15. Then create two projects with these two new water points. Other project settings are the same as the settings of the default project in Section 5.4.1. Then run the projects to get the production frontiers and view the results.

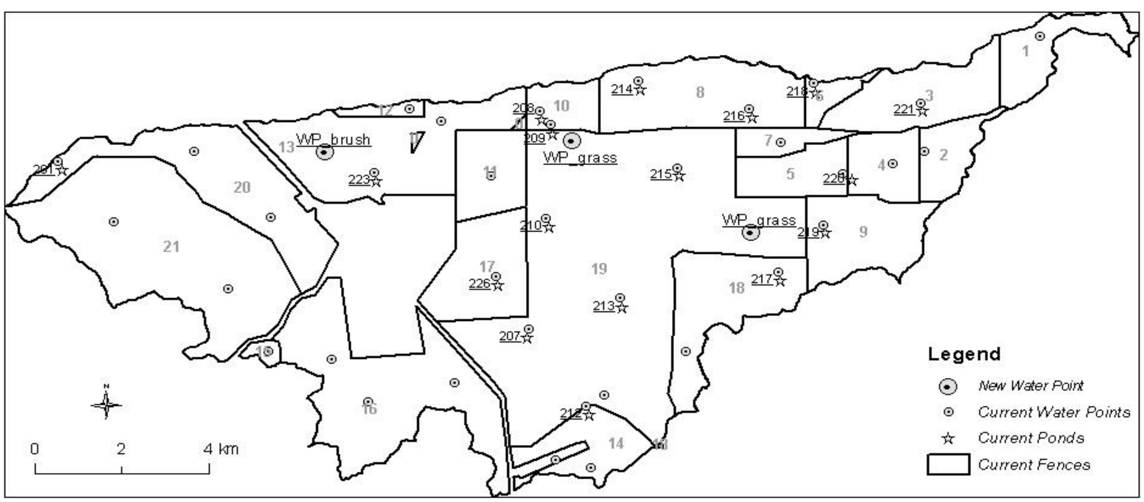


Figure 5-15 Map of new water points in Application 3

Results

The results show that either project with new water points is inferior to current operations (Figure 5-16). The current operation dominates either project with new water points at all range. Since the ranch already has dense water points, the forage increase from new points cannot compensate for the cost of the new points. The project with WP_grass includes two new water points and the project with WP_brush includes one new water point, so the curve of WP_grass is lower than the curve of WP_brush. It is not cost effective to add new water points in the pastures with dense water points. However, the new water points do increase carrying capacity and provide more flexibility in controlling sediment yield (Figure 5-16).

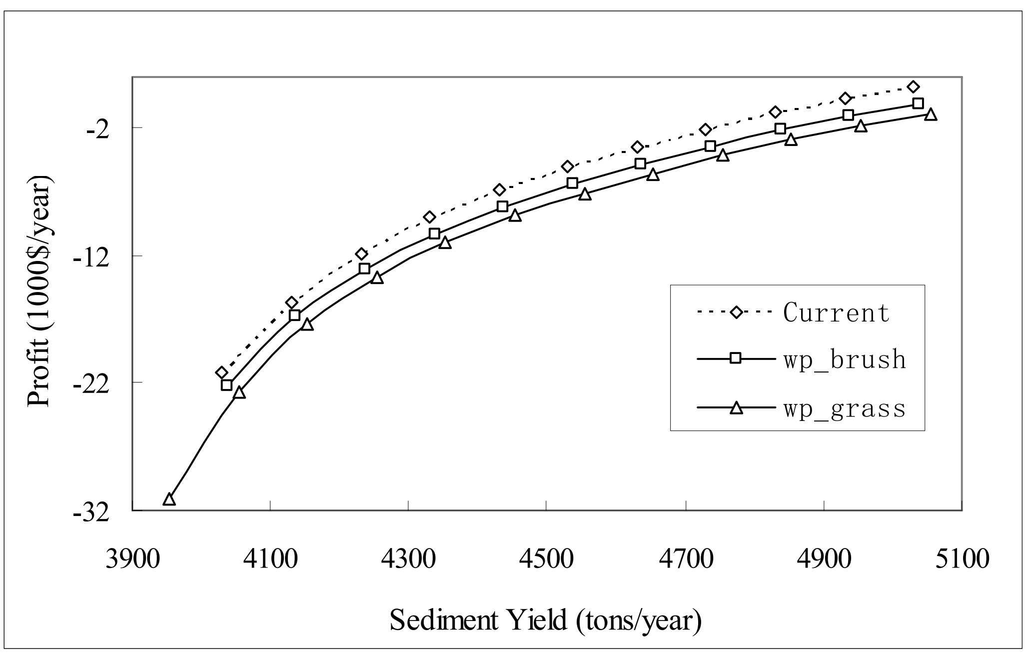


Figure 5-16 Production frontiers of the projects with the new water points at different locations.

5.4.4. Application 4: Reducing Sediment Yield by Adding Stock Ponds

Objective

Stock ponds are structures to detain sediment. Several factors may affect the effectiveness in pond sediment detaining efficiency. This application illustrates the impacts of different ponds in reducing sediment yield. The factors considered include three categories:

- Location in the watershed, downstream, middle or upstream.
- Vegetation type, brush or grass.
- Erosion potential, high erodibility or low erodibility.

Procedure

Create five new pond layers in the map editor. The locations of new ponds are shown in Figure 5-17. Then create the new projects with each new pond layer. Other settings of the projects are the same as the default project in Application 1. Then run the projects to get the production frontiers and view the results.

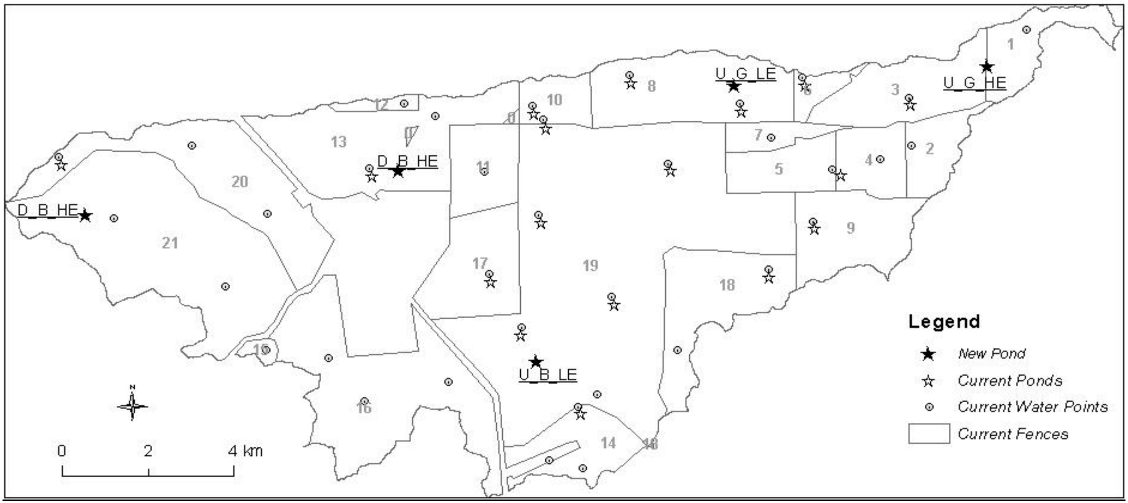
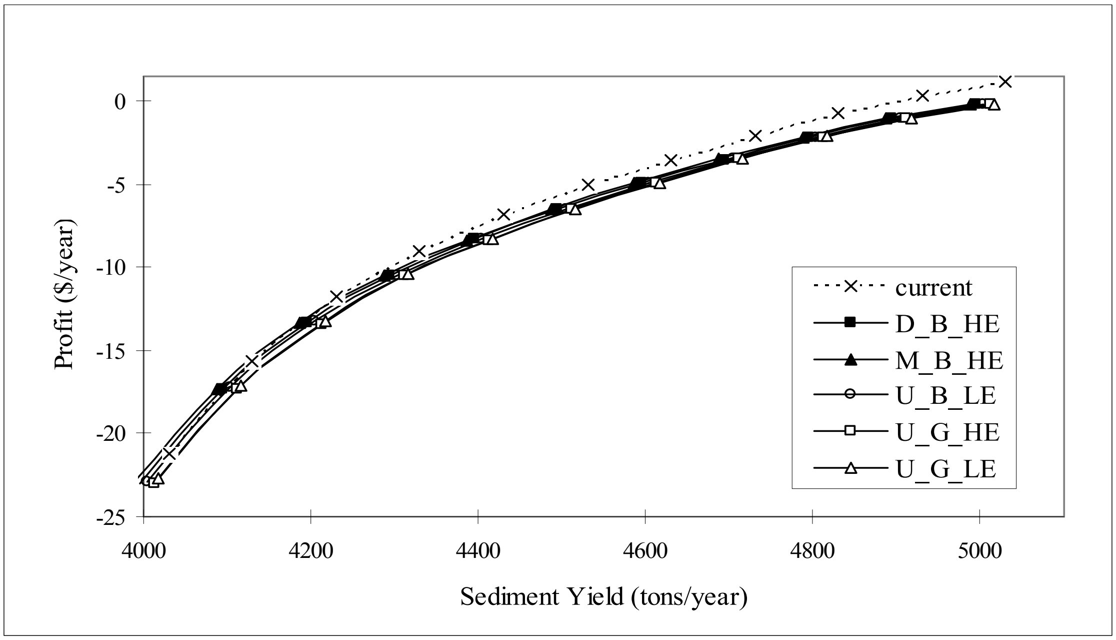


Figure 5-17 Map of new ponds in Application 4

Results

The production frontiers under current conditions and with new ponds are shown in Figure 5-18. The production frontier under current conditions dominates all other projects with new ponds at most sediment yield levels and the curve crosses other production frontiers only at very low sediment yield, which implies that sediment yield reduction by ponds is inferior to reducing grazing intensity from an economic perspective. In other words, the reduction of grazing intensity costs less than building new ponds. However, the new ponds do reduce the peak sediment yield on the curve.

Pond locations and vegetation types may affect sediment yield. The ponds reduce more sediment yield downstream than the pond at the upstream. This may be caused by the fact that a higher percent of sediment from upstream is detained before reaching the outlet than that from downstream according to the model assumption. Ponds on highly eroded brush lands might detain more sediment than those in grass lands with low erosion during same period. However all these statements are made on this special case and the exact impacts should be estimated from models because many factors affect the complex process of erosion and sediment.



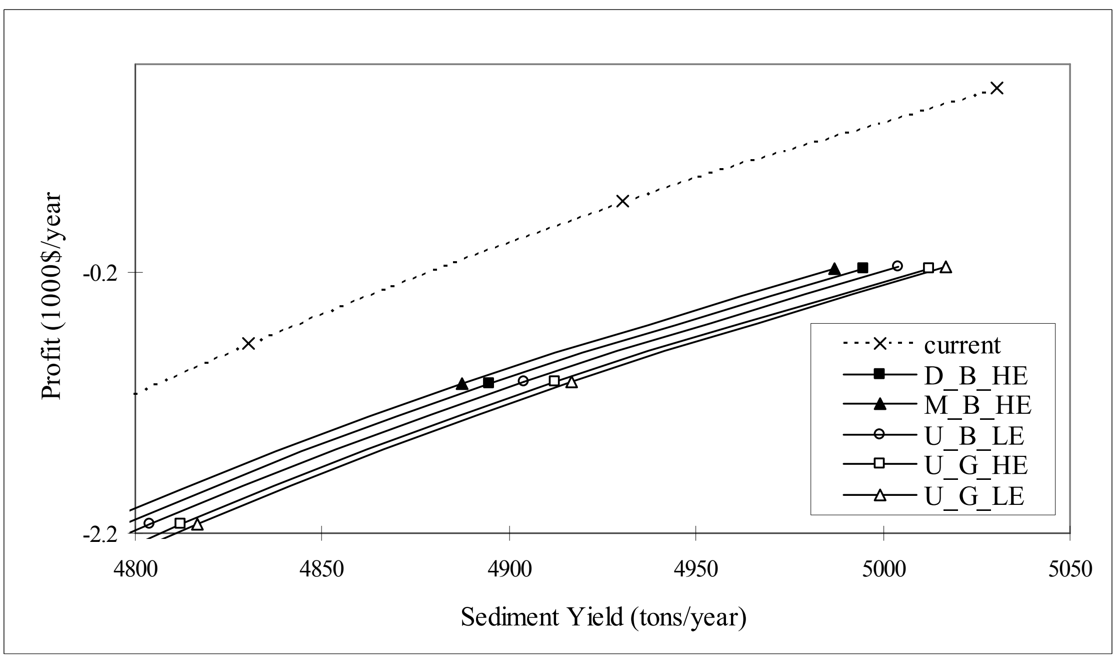


Figure 5-18 Production frontiers of the projects with new stock ponds. In the legend, D, M and U refer to the down middle and up stream of the pond location; B and G refers to brush and grass, the dominant vegetation types of the control areas, HE and LE are the high and low erosion potential of the control areas. The first figure is the magnified top right of the first figure and the third figure is the magnified top right of the first figure.

5.4.5. Application 5: Reducing Sediment Yield through Improving Ecological Condition

Objective

Ecological condition is an important factor in determining grazing capacity and erosion rate on rangeland. Rangeland in better ecological condition can support a higher carrying capacity and still maintain sediment yield at a lower level. This example illustrates how the SDSS may be used to assess ecological condition improvements.

Procedure

Create four projects with the four ecological conditions, poor, fair, good and excellent respectively. The other settings are the same as the default project in the first application. Then run the projects to get the production frontiers and view the results.

Results

The results show that ecological conditions significantly affect carrying capacity and sediment yield (Figure 5-19). For the same stocking rate, the sediment yield at better condition is much lower. The reduction of sediment yield from improved ecological conditions is more significant than other measures, such as reducing grazing intensity or adding new infrastructure. The results also show that the ranch with a better ecological condition and moderate grazing intensity created less sediment yield than the same ranch with a worse condition and no grazing.

At present, this SDSS does not support the assessment of range improvements directly. However, an indirect approach can be used to assess the costs and benefits of ecological condition improvements. For example, in Figure 5-19, if a practice can improve the ecological condition from fair to good, the ranch operation will shift from A to B, then the profit increases ΔP and the sediment yield decreases ΔSY. If the annualized cost of an improved practice is less than the increased profits, then the practice improves not only the ranch's economy but also the environment.

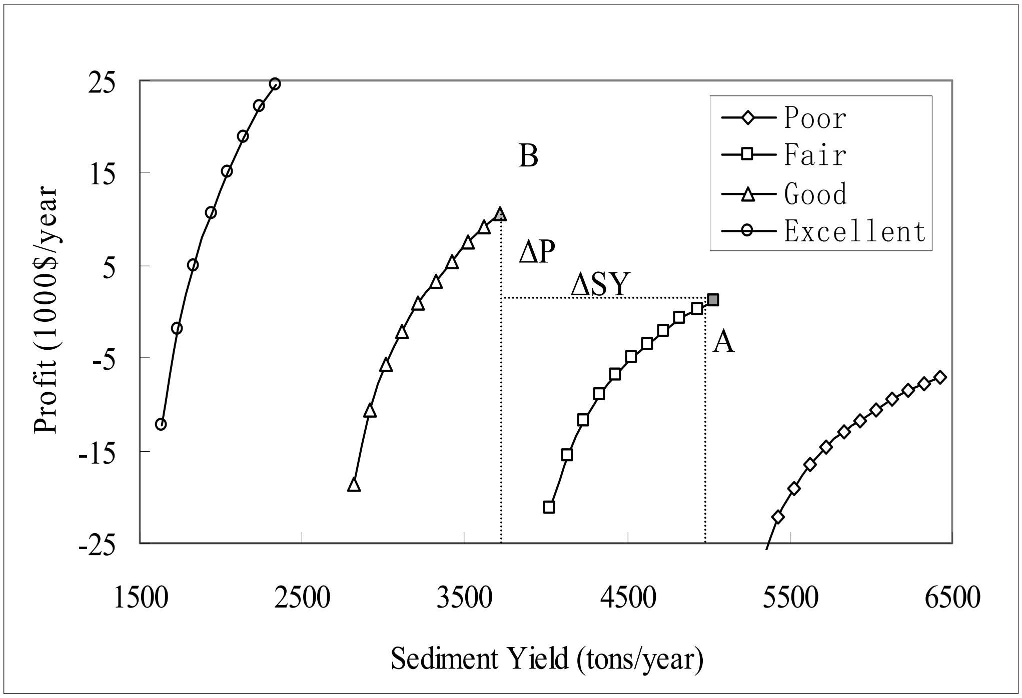


Figure 5-19 Production frontiers of the projects under different ecological conditions

5.4.6. Application 6: Assessment of the Effectiveness of Cost Sharing

The requirement to reduce sediment yield can cause economic burdens to ranchers either by reducing stocking rate or by increasing input costs. The applications in Section 5.4.3 and 5.4.4 showed negative economic impacts of adding water points and ponds. Such impacts may discourage ranchers from participating in a TMDL program. Government can provide financial aid to encourage ranchers to participate in such projects. The policy of cost sharing of infrastructure construction is an incentive-based policy instrument that may reverse the negative economic impacts on ranchers. This application illustrates how this SDSS may be used to assess the economic impacts of different levels of cost sharing of pond and water point infrastructure. The results are useful to determine the proper cost sharing level for sediment control objectives.

Procedure

Using the two water point layers of WP_grass and WP_brush in Figure 5-15, create six projects with water point cost sharing levels of 0%, 50% and 100%. Then run the projects to get the production frontiers. Similarly, using the pond layers of D_B_HE and U_G_HE in Figure 5-17, create six projects with pond cost sharing levels of 0%, 50% and 100%. Then run the projects to get the production frontiers. View these results.

Results

The results of the six projects with new water points show that the production frontiers move upward with increasing cost sharing. The 100% cost sharing provides the highest profit return. The project with 100% cost sharing of water points on grasslands provides a higher return than the project with 100% cost sharing of water point at brush lands. The new water point provides more carrying capacity, consequently increasing sediment yields. From the sediment control perspective, financial aid on water point projects seems incompatible with sediment control objectives. However, the new water points allow more flexible grazing adjustments.

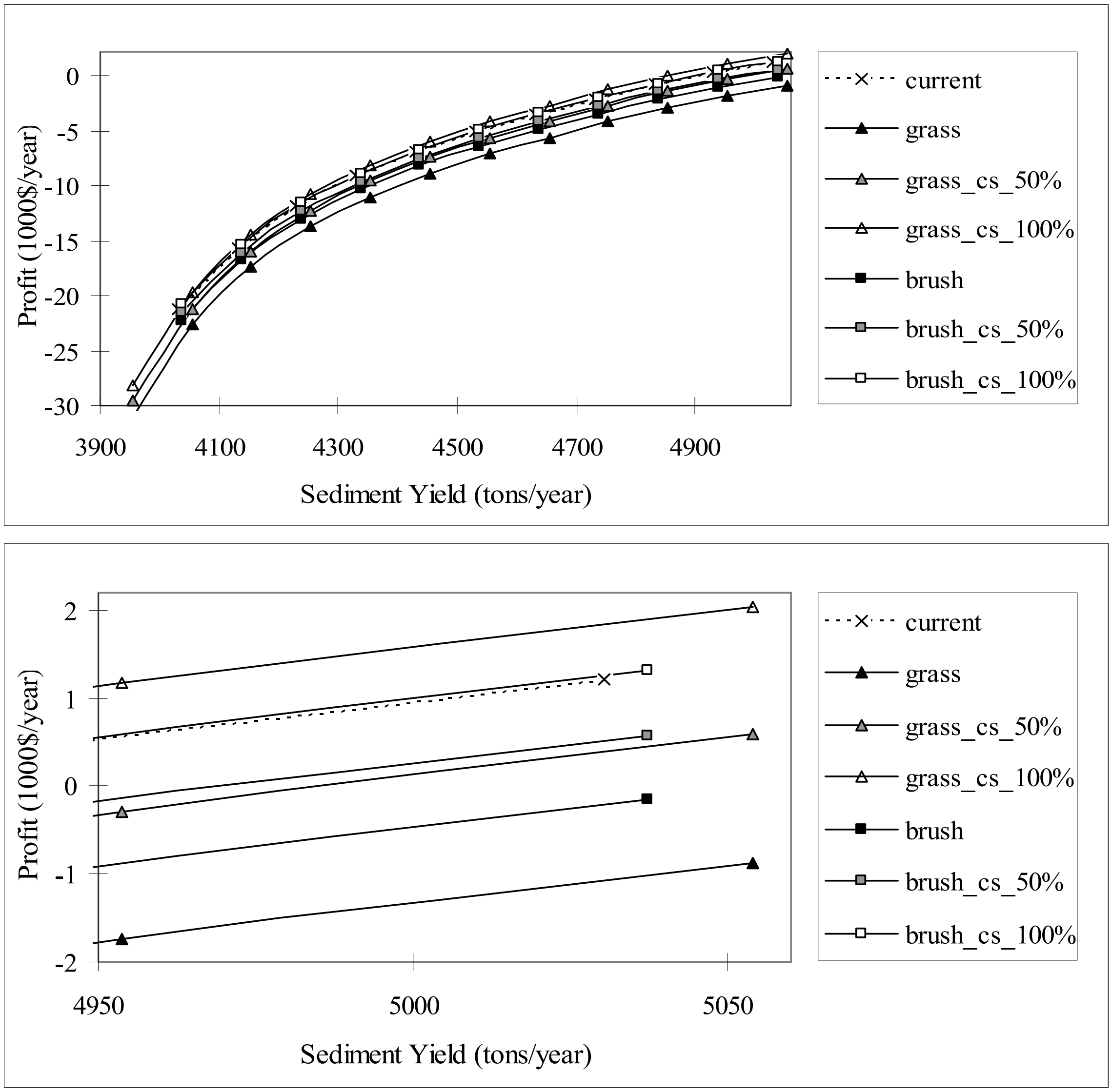


Figure 5-20 Production frontiers of the projects with the new water points and cost sharing at 0%, 50% and 100%. The bottom curves are the magnified top right part of the top figure.

Similarly, the production frontiers of the projects with new ponds move upward with increasing cost sharing percents (Figure 5-21). However, the curve shapes are different from the curves of the projects with the new water points. The sediment yield corresponding to the highest profit with new ponds decreases about 20 - 40 tons/year.

The 100% cost sharing of pond construction cost does not provide full compensation for the extra maintenance cost of new ponds. Furthermore, constructing new stock ponds cannot improve ranch revenue as assumed in current SDSS model.

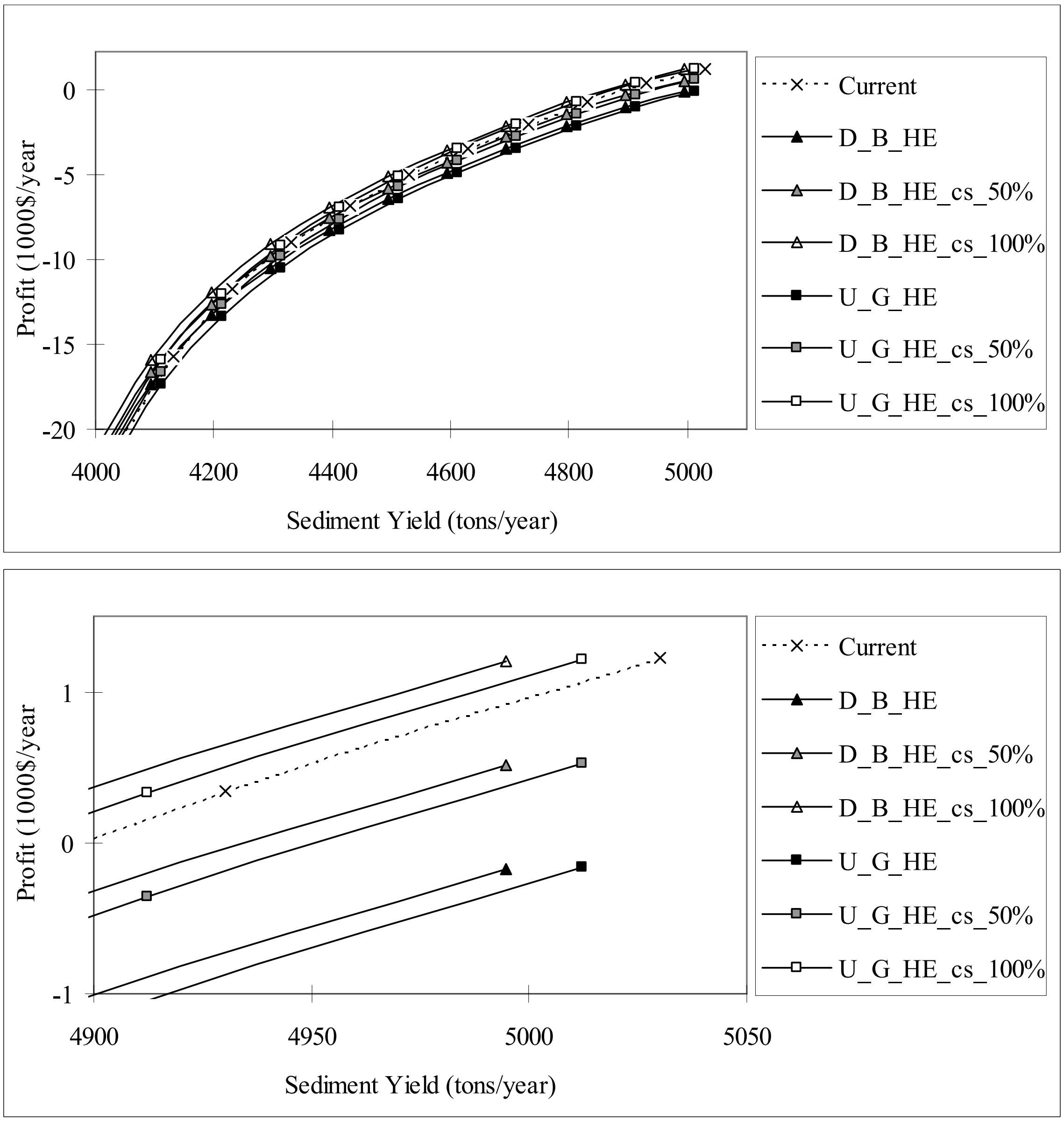


Figure 5-21 Production frontiers of the projects with the new ponds and the cost sharing of 0%, 50% and 100%. The second figure is the magnified right top part of the first one.

5.4.7. Application 7: Comparison of Management Combinations

Objective

A TMDL plan usually consists of different managements and/or policy options. Decision makers have several feasible options and need to select the best one according to defined criteria. This application illustrates how the SDSS could aid in ranking different options of management combinations.

Procedure

Create two fence layers, Fence_1 and Fence_2, as shown in Figure 5-22. The new fence configuration, named Fence_1, segments two pastures roughly along the border of two ecological sites in Pasture 7 and 21 respectively. The other new fence configuration, Fence_2, segments the largest pasture, Pasture 19, into three pastures. Create two water point layers, WP_1 and WP_2, as shown in Figure 5-22. Create two new projects. One project, Com1, uses Fence_1 as the fence layer, WP_1 as the water point layer and D_G_HE as the pond layer. The other project, Com2, uses Fence_2 as the fence layer, WP_2 as the water point layer and U_G_HE as the pond layer. For these two projects, also create the new projects with 50% and 100% cost sharing of the cost of the new infrastructures respectively. Then run the projects to get the production frontier and view the results.

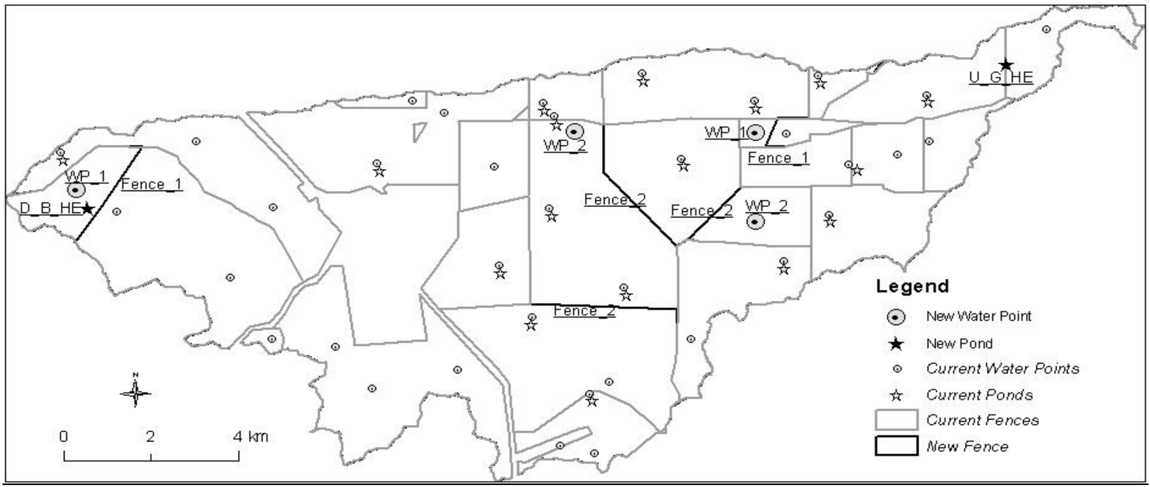


Figure 5-22 Map of the infrastructure of two management combinations

Results

The production frontiers are summarized in Figure 5-23. The production frontiers for both projects without cost sharing are far below the production frontier of the default project. The main reason is that the new infrastructures for the two projects have a huge cost. Because Com2 adds much longer fences, the curve of Com is below the curve of Com1. The increase of the carrying capacity from new infrastructure is insignificant compared with the associated costs. Cost sharing reduces the ranch's cost to implement these structures. With 100% cost sharing, Com2 has higher profits than the current operation and higher sediment yield. The high cost of the infrastructure cause these practices to be less cost efficient approaches in reducing sediment yield.

However, fences are the infrastructures that allow better grazing plans. The better grazing rotation may help to recover overgrazed area and improve the ecological condition. These impacts are not considered in current models as the quantitative relationship of the impacts is unavailable.

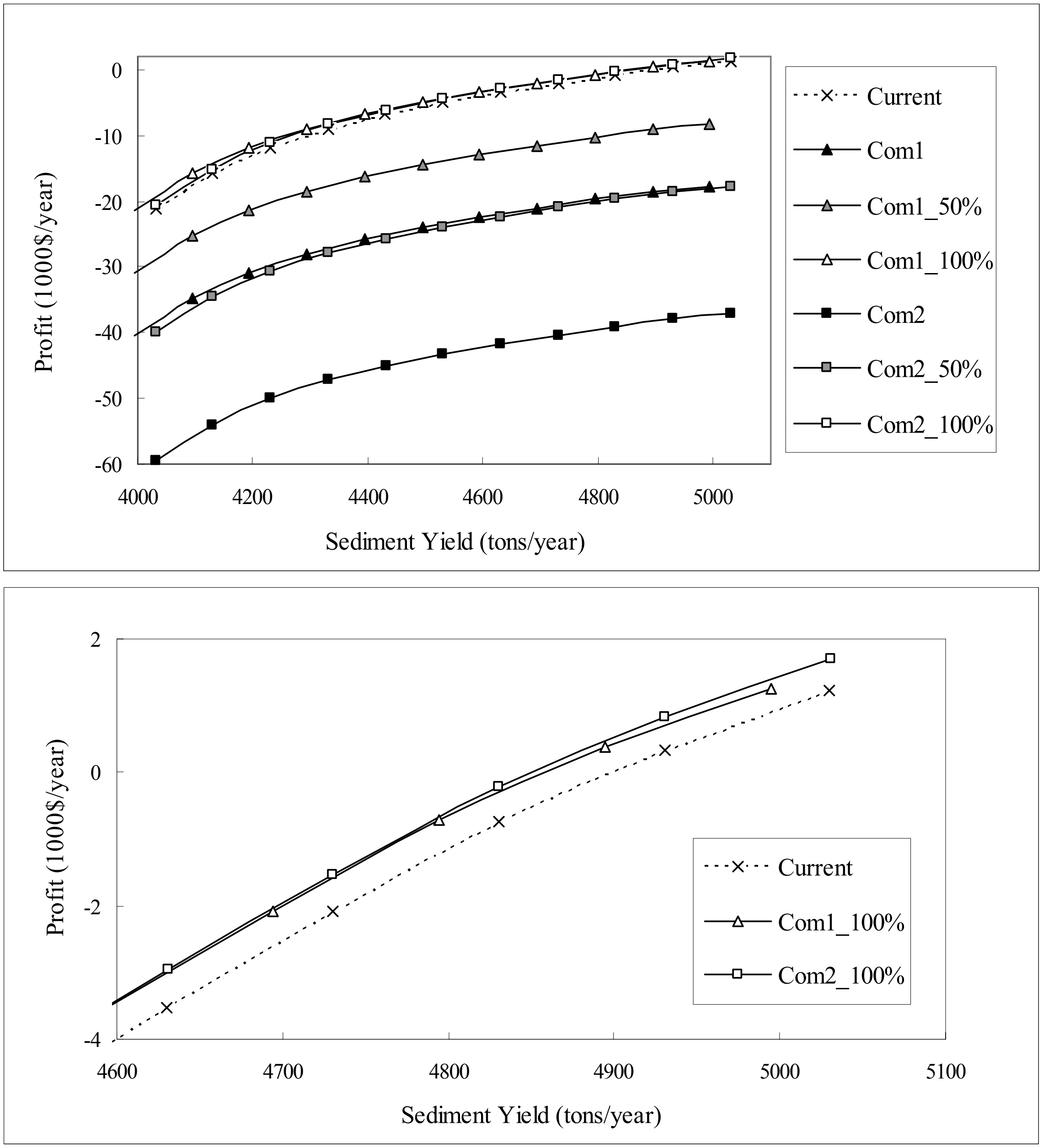


Figure 5-23 Production frontiers of the projects with two management combinations and the cost sharing 0%, 50% and 100%. The second figure is the magnified top right part of the first figure.

5.4.8. Application 8: Adaptive Management of Climate Variation Using the Dynamic Model

Objective

Previous applications used the static model. The climate was assumed constant during whole planning period. The SDSS also support the dynamic models to solve the optimization problem of multi-year managements with varying climate. This application illustrates how ranch management may adapt to climate variations to meet the profit objective and the sediment control requirement.

Procedure

Create four projects with default settings in Section 5.4.1 except setting a five-year planning span with four climate patterns: NNNNN, NNWNN, NNDNN, and NWNDN. N is normal climate, W is wet climate, D is Dry climate, and each capital character represents the climate of a year. For each climate pattern, first run a project without sediment constraints, and then create a new project with a 10% reduction of the maximum sediment yield.

Results

The dynamic model gives very similar results compared to the static model using the default settings (Table 5-1). The erosion and sediment yield of the dynamic model are a little higher than in the static model. The profits from two models are different as they use different methods to calculate the revenues and the costs.

Table 5-1 Comparison of the static and dynamic results under default settings

	Herd Size (cow/calf pairs)	Erosion (tons/year)	Sediment yield (tons/year)	Profits ($/year)
Static model	276	15890	5030	1221
Dynamic	277	17037	5372	-3102

Climate can significantly change the carrying capacity and the sediment yield (Figure 5-24). For the five-year homogeneous normal climate pattern, the herd size, profits and sediment yield are stable in the five years. Under a varying climate pattern, the herd size increases in wet years and decreases in dry years. The profits change with the corresponding the adjustments of herd size. The sediment yield results show the same pattern of climate changes. Drought can significantly decrease the carrying capacity of the dry year and the following year.

The sediment yield control requirement reduces the grazing intensity and also profits for all scenarios. With the 10% sediment yield reduction, the herd size decreases tens to hundreds depending on climate patterns. The net present value of losses of 10% sediment reduction are $37228, $52143, $42028 and $51847 for the climate pattern NNNNN, NNDNN, NNWNN and NDNWN respectively.

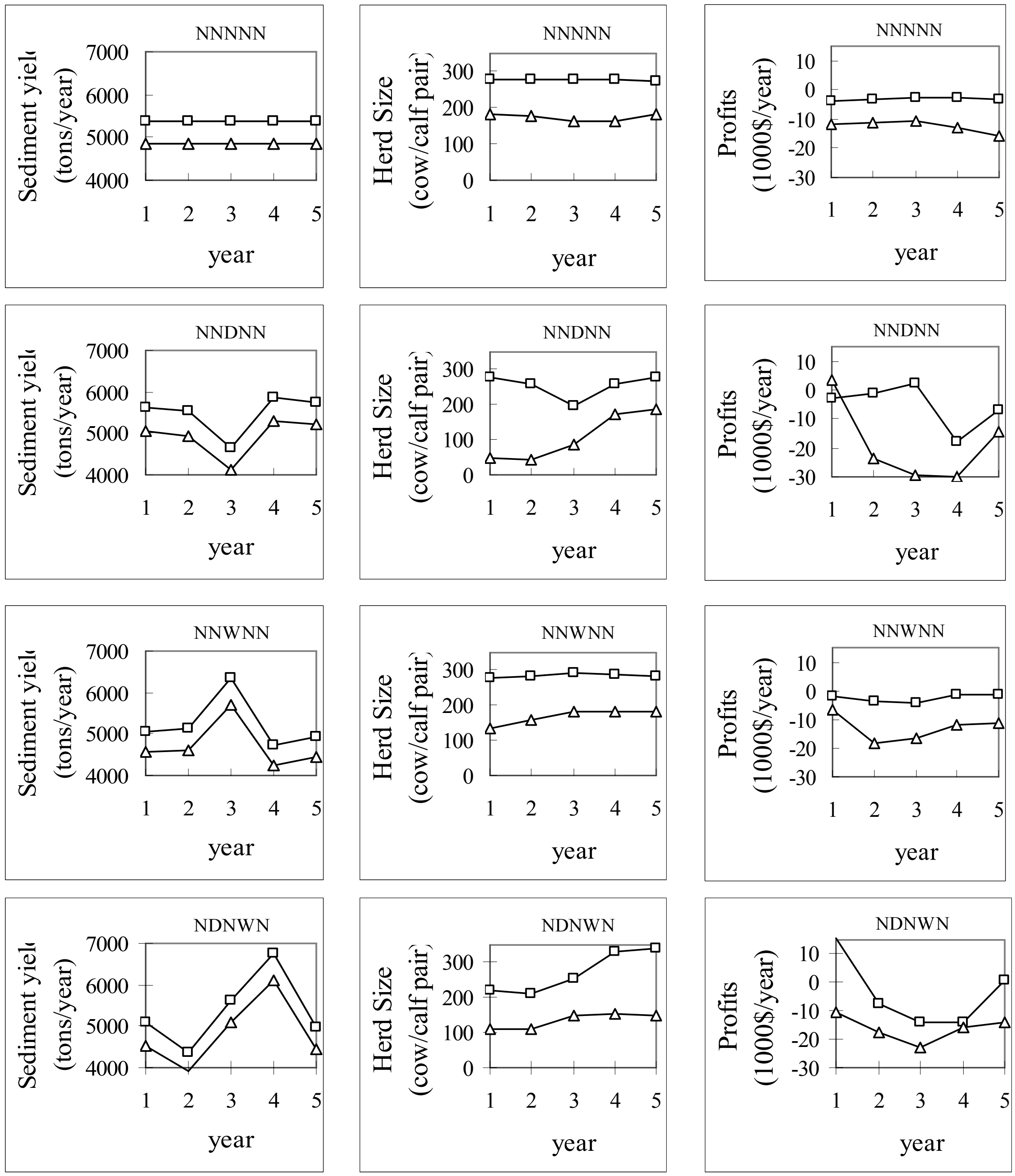


Figure 5-1 Dynamics of ranch operation under different climate patterns and sediment control level. Rectangle series is without sediment control and triangle series is with 10% sediment reduction. Climate series: N is normal, D is dry, W is wet.

A dry climate will cause higher loss to the ranch. In particular, dry climate causes more binding constraints in the planning period. Furthermore, a wet year after a drought usually causes higher erosion due to lower cover. In such a climate pattern, in order to meet the sediment yield objectives, the stocking rate must be reduced significantly to keep enough biomass left to protect soil. In practice, climate is unknown at the beginning of a year and ranchers need take a conservative grazing strategy to reduce the negative impacts from possible drought.

5.5. Policy Implications

Rangeland biomass on different ecological sites of a watershed varies in both economic and soil conservation value. This variation provides an economic justification for forage planning and management on the watershed level. The watershed-based economic optimization models provide a tool to aid in making the trade-off. The case study of Walnut Gulch Watershed illustrates this type of analysis. An efficient plan is possible to reduce the sediment yield.

It may be difficult from legal and economic perspectives to enforce conservation on grazing land. Because ranching is a traditional land use of rangeland and currently the economic status of ranches is stressed, an effective TMDL plan needs to carefully design policy instruments to relieve the possible negative impacts on ranchers.

An incentive-based policy is a practical way for effective policy. Two policy instruments may be important. The first one is cost sharing. Cost sharing is widely used in public land management. The public land management agencies provide financial support for ranchers to build infrastructure, such as fences, water points, etc., to maintain rangeland condition. However, current cost sharing policy was designed for maintaining ecological condition. The magnitude of current policy may not be enough to meet the sediment objectives of a TMDL plan. By incorporating the impacts of sediment reduction into a decision, new designed schemes of cost sharing policy could be more effective in meeting the sediment yield control objective. The new scheme could provide more support for range condition improvement and erosion reduction practices. Since the current cost sharing policy is managed by several public land agencies, defining the responsibilities and coordinating the different agencies on watershed level is a challenging job.

The second type of policy is to manage carrying capacity more efficiently. Current stocking rates are defined on the estimation of long-term average forage supply. Actual carrying capacity of a pasture will change with time. Furthermore, each land parcel has different watershed values, such as sediment yield contribution. Ranch management could be improved if all these factors are considered in ranching plans. The public land management agencies should provide incentives for ranches to take environment friendly grazing strategy. For example, a public land agency can reduce or retire part of grazing lands with low production and high erodibility, and public land agency can require ranchers to reduce stocking rates at the early stage of a drought. On public land, stocking rates and can be enforced without compensation, which implies less implementation cost for such lands.

5.6. Summary

This chapter made a case study of the SDSS for the Walnut Gulch Watershed. The parameterization section described the major data inputs and preprocessing of spatial layers. The validation showed that the model prediction roughly matches the current observed data. However, more detailed observed data are needed to calibrate and validate the model for better prediction. Eight application examples were used to illustrate how the SDSS could assess the impacts of different managements from the economic and environmental perspectives. The sample results showed that infrastructure, such as new fences, water points and ponds, are less cost-effective tools than adjustment of stocking rate with the current infrastructure and price level.

CHAPTER 6 SUMMARY

Watershed management is the major approach in TMDL development to protect water quality from non-point source pollution. A TMDL plan for a watershed needs to select the best option from different management alternatives. The critical point for successful decision making is to coordinate several interest groups into a cooperative team to improve the environment. To realize the cooperation, the first step is to help all participants understand the role of each group in watershed conservation and how their action can affect the watershed environment.

A web-based spatial decision support system can be a useful tool for this purpose. A watershed analysis requires spatial and non-spatial inputs. It also requires complicated procedures to transform inputs into proper outputs that can be used in decision making. The web-based SDSS provides several advantages for this type of application. The system allows researchers to more efficiently distribute various data, such as maps and economic parameters, and research advances, such as simulation models. The web-based system allows sharing of data and analytical tools across the user community. In particular, the system allows inexperienced users to perform watershed analysis, which is impossible without such a system, because of the hardware, software or experience limitations.

An SDSS is critical for improving rangeland watershed management. Compared with croplands, rangeland is mainly public lands that are monitored and managed by the government agencies. These government agencies have collected data on rangeland conditions. However, little effort has been devoted to rangeland modeling because of its low economic value per unit area. With increasing concern about the water quality issues in rangeland, the SDSS was developed to provide such a tool in distributing data and providing analysis for rangeland watersheds that are the dominating landscape in the western USA.

This chapter includes five sections. The first section summarizes the contents of this study. The second section describes the major contributions of the study. The third section lists the major limitations of this study. The fourth section states the major conclusions of the study. The final section describes the recommendations for future research.

6.1. Summary

The objective of this study is to develop a SDSS for economic assessment of different management practices to reduce sediment yield on rangeland watersheds. This dissertation describes the SDSS development, including the study objective and requirements, literature review, the model development, SDSS design and the case study. The introductory chapter defined the study objectives after the introduction of the study background. Then the approaches to implement the SDSS and the possible benefits were also discussed.

Chapter 2 reviewed the literature on three related topics. The first topic is current research in bio-physical processes on rangeland watersheds, including plant growth, livestock grazing and erosion processes, with emphasis on sediment modeling on the watershed level. The second topic is the economics of range and watershed management, including the major economic methods and mathematical modeling in these two fields. The third topic is DSS in natural resource management, including DSS in range management, DSS in watershed studies, SDSS and web-based DSS.

Chapter 3 described the bio-economic model development. The management problem in a rangeland watershed was modeled as an optimization production problem of a representative ranch that is assumed to use all grazing land in a watershed. The model used basic units representing the spatial heterogeneity. Each basic unit was assumed to be homogeneous in vegetation production and erosion. There are two major types of models, static and dynamic. Each model has six components to represent the major elements in a rangeland system. The plant component defined two vegetation types, grass and brush. Biomass production was estimated from the ecological climax production and adjusted with climate, ecological condition and grass utilization. The distribution of livestock grazing was simulated through two methods, Range Map and a regression equation. The models used the forage utilization constraints to define the sustainable grazing requirement. Upland erosion was predicted from the embedded RUSLE2 equation. The sediment yield was estimated from erosion and sediment delivery ratios. The total sediment yield was constrained by the control objective. In the economic component, the ranch revenue was from the sale of livestock and the associated cost includes variable, fixed and environment conservation costs. The objective of ranch operation is to maximize the profit while meeting the constraints. The functions in the static model are based on long-term relationships. The dynamic model added the temporal dimension to the model configuration and used differential equations to represent biomass and livestock conversion, and environmental impacts of different management plans. GAMS was used to solve these models. Possible extensions of the models were also discussed in this chapter.

Chapter 4 described the SDSS interface design and system integration. The architecture of the SDSS includes three tiers, the interface, process and data tiers. The interfaces are the dynamic web pages created from JSP/Servlets that support customized input editing, watershed analysis implementation and result visualization in the web pages. The process tier defined the procedures for watershed analysis, such as map generation, optimization model implementation and result storage. The data tier used the ORACLE database to manage all the data. Files were used to store spatial data and communicate between processes. All these parts were integrated by the Servlet middleware. The chapter also described the procedures for typical analysis step by step. The parameterization of the SDSS and the extension of the SDSS were briefly discussed in the final section of this chapter.

Chapter 5 made a case study for the Walnut Gulch Watershed. Following a brief introduction of the study area, the chapter described the parameterization of the SDSS and the preliminary validation of the models. Then eight sample applications were used to illustrate how the SDSS could be used in assessing and comparing different management and policy options from an economic perspective.

Chapter 6 summarizes this dissertation, including the major contributions, conclusions, limitation and recommendations for future studies. The appendices include various supporting materials, including program code, parameters, sample outputs, SWAT simulation and screen captures of the SDSS interfaces.

This study meets the study objectives defined in Chapter 1. The embedded models in the SDSS provide an integrated ranch production model that predicts both economic and sediment outputs with different management on the watershed level. A database was designed and implemented to manage all information in the SDSS. The models and database were integrated with the interfaces in the SDSS application. The SDSS can assess several major best management practices on rangeland. The SDSS allows users to create inputs, to define sediment control objective and to view the results. The SDSS system was implemented for the Walnut Gulch Watershed and sample applications showed the major functionalities of the SDSS.

6.2. Major Contributions

This dissertation developed a prototype SDSS intended to aid rangeland watershed analysis from an economic perspective. The contributions of this study to the literature can be summarized in three aspects.

The first aspect is the economic optimization model development. The models use the basic units representing the spatial configuration of a watershed. This configuration considers the characteristics of vegetation production, grazing management and hydrologic units. This configuration can represent the spatial heterogeneity while keeping the number of land units within a reasonable size. The models incorporated the functions of vegetation production, livestock grazing and erosion in a system. The models can spatially optimize grazing to meet the production objective, the forage utilization objective and sediment control objective. The models are nonlinear. Since most rangeland relationships are nonlinear, this model setting allows more accuracy in representing the rangeland processes. In addition, the SDSS also supports analysis of diverse relationships through different model types.

The second aspect is that the SDSS supports watershed analysis through customized web pages. The system provides the embedded data shared by all users for easy startup. At the same time, the system allows users to create their own data for advanced analysis. The system is a thin-client web application. Users only need a web browser to perform watershed analysis without programming GIS and optimization models. This feature greatly reduces the requirements for inexperienced users to implement a watershed analysis application. The web-based dynamic map service provides an efficient way to create spatial inputs and to view spatial outputs of watershed applications.

The third aspect is the analysis functionality. The SDSS can automatically compute the spatially optimum management, production frontier and abatement cost curves through the embedded models. The comparison of the production frontiers of different infrastructure provides a robust ranking of different management options. Furthermore, the model also supports cost sharing policy analysis that is useful in assessing the economic incentives for ranchers to implement conservation practices.

6.3. Limitations

The study developed a prototype SDSS that could be used to aid in rangeland watershed management. However, rangeland watershed management is complex and range processes are not well understood, thus the study has several major limitations.

The first limitation is the vegetation simulation. Vegetation production can vary with climate, soil, topography, season and many other factors. Different species also show great differences in growth behavior. The spatial and temporal pattern of grazing may significantly change the composition and potential of the vegetation community. In addition, grazing and other practices may have long-term impacts on shifting rangeland ecological conditions. For example, good grazing rotation may recover a pasture from fair to good condition. These impacts, especially the interactions with climate and management, are not well understood, and thus are not incorporated in the SDSS models. The simplification makes the model unsuitable for a sophisticated study of long-term detailed vegetation dynamics.

The second limitation is the application scope. The model used several empirical functions to define the relationships of rangeland processes. Since these relationships were derived from certain geographic areas, one should be careful in extending the model to other areas. Substantial effort may be needed to extend the model to other geographic areas.

The third limitation is the hydrologic and erosion process simulation. The hydrologic processes were not explicitly included in the models. Sediment delivery ratios were used to compute sediment transportation. The method has two major problems. The first problem is to define a proper procedure to estimate the sediment yield ratio map of a watershed. The second problem is the applicability of sediment delivery ratio in sediment yield estimation. For example, what factors may affect the sediment delivery ratio of a location and to what extent do the ratio values may vary at a site? Current literature does not give a satisfying answer to these questions. In particular, channel processes are important factors in determining the sediment yield, which are assumed to be constant and based on a very simple model. In a word, a rangeland erosion prediction model is needed for such application. The specially designed model would greatly improve the reliability of SDSS prediction.

The fourth limitation is the limited set of management options supported by the SDSS. The SDSS only supports four management options, grazing intensity, fences, water points and stock ponds. These are only a small part of the list of the best management practices. This limitation may restrict the application of the SDSS.

The fifth limitation is that the study models the whole watershed as a representative ranch. A watershed usually contains several ranches. This model setting cannot show the distribution of impacts among ranches across a watershed. The distribution of impacts among different ranches may be important in planning and policy design. Furthermore, the model excludes the areas that are not grazed lands. If the conversion from grazing land to urban area is a major issue, the current model cannot support such analysis.

Finally, the SDSS requires maintaining a central server system to provide the web service. The cost associated with setup and maintenances of the SDSS may be high. For this type of application, commercialization seems unlikely. Thus financial issues become critical to maintaining such a system.

6.4. Conclusions

This dissertation developed a prototype spatial decision support system for rangeland watersheds. The embedded models are the core that provides the watershed analysis functionality. The rangeland management problem was formulated as nonlinear optimization models for the complex rangeland system. The spatial structure of a watershed was represented by basic units. The component-based structure was used in modeling the rangeland system so as to be easy in modeling, updating and integrating. The diverse model types provide the SDSS the ability to addressing problem using different rangeland relationships.

This SDSS can implement a watershed analysis in a web environment. The three-tier architecture seamlessly organized the interface, data and process into one application. The database is the core part to manage all information of the applications. The customized interfaces provide users easy access to different functionality. The embedded processes provide the watershed analysis functionality. The thin-client web application can provide the convenient access for this application.

The case study for the Walnut Gulch Watershed illustrated the functionality of the SDSS. Most data used in the SDSS parameterization are widely available. The sample analysis showed that the sediment yield could decrease in the short run by reducing the stocking rates. The economically efficient way to reduce sediment yield is to first reduce the stocking rate near the outlet, then the reduction should shift to upstream areas with an increasing sediment control objective. On the Walnut Gulch Watershed, adding new infrastructure is not as cost effective in reducing the sediment yield as reducing stocking rate. However, a cost sharing policy can reduce ranchers' cost and make new infrastructure desirable to ranchers under a high compensation level. Other factors, such as climate and ecological condition can also significantly affect production frontiers. These sample applications illustrate that the production frontiers provided a robust approach to rank different management options.

6.5. Recommendations for Future Research

The study of spatial decision support systems for economic analysis of sediment control on rangeland watersheds is still developing. Several aspects are particularly important in future research.

The first aspect is to standardize the framework of watershed management problems. In current watershed management research, each study defines its own spatial configuration, components, process and management. The diversity of problem settings makes it difficult to share the analysis tools and to compare the results from different research. Only if there is a common foundation can researchers cooperate in building, improving and calibrating models for generalized watershed problems.

The second aspect is to improve rangeland modeling. The literature on rangeland modeling is less voluminous and developed than on cropland. Calibrated and validated models for rangeland watersheds are scarce. Because simulation models are important sources in understanding the rangeland processes, the lack of reliable models for rangeland watershed makes the analysis more difficult to implement and results highly uncertain. Thus, more research is needed in rangeland watershed modeling and validation, particularly on erosion and sedimentation problems.

Furthermore, management-oriented applications require sophisticated vegetation simulation and diverse management options that are ignored in many watershed models.

A promising development in rangeland is the state and transition model (Bestelmeyer et al. 2003). Once state and transition models have been developed, they should be used to incorporate management efforts on vegetation. When a comprehensive spatially distributed rangeland simulation model becomes available, it should be incorporated into the SDSS. In addition, more observed data of the sediment budget on different scales, from plot to watershed scales, are needed to define initial conditions and calibrate the model.

The third aspect is to improve the SDSS design. Information technology development provides high potential for more sophisticated web-based applications. A SDSS should be a platform that provides efficient links among researchers and general users. The platform could efficiently distribute various data and diverse analytic models to users. Because the SDSS is application-oriented, users' requirements are the most important criteria in the SDSS design. More studies are needed to define the standard functionalities based on wide user surveys. With standardized functionalities, models can be incorporated into the SDSS through middleware that allow the SDSS communicate seamlessly.

The fourth aspect is the system efficiency. The SDSS uses individual processes to activate the GIS processing and optimization models. Because these processes are time-consuming, the system performance may be reduced when several processes are running in the same machine. If these long-transaction requests can be processed on a separate machine, the main server can respond to users' request faster. In summary, the separation of system functions can improve the system response and make the system maintenance easier.

APPENDIX A MODEL STRUCTURE

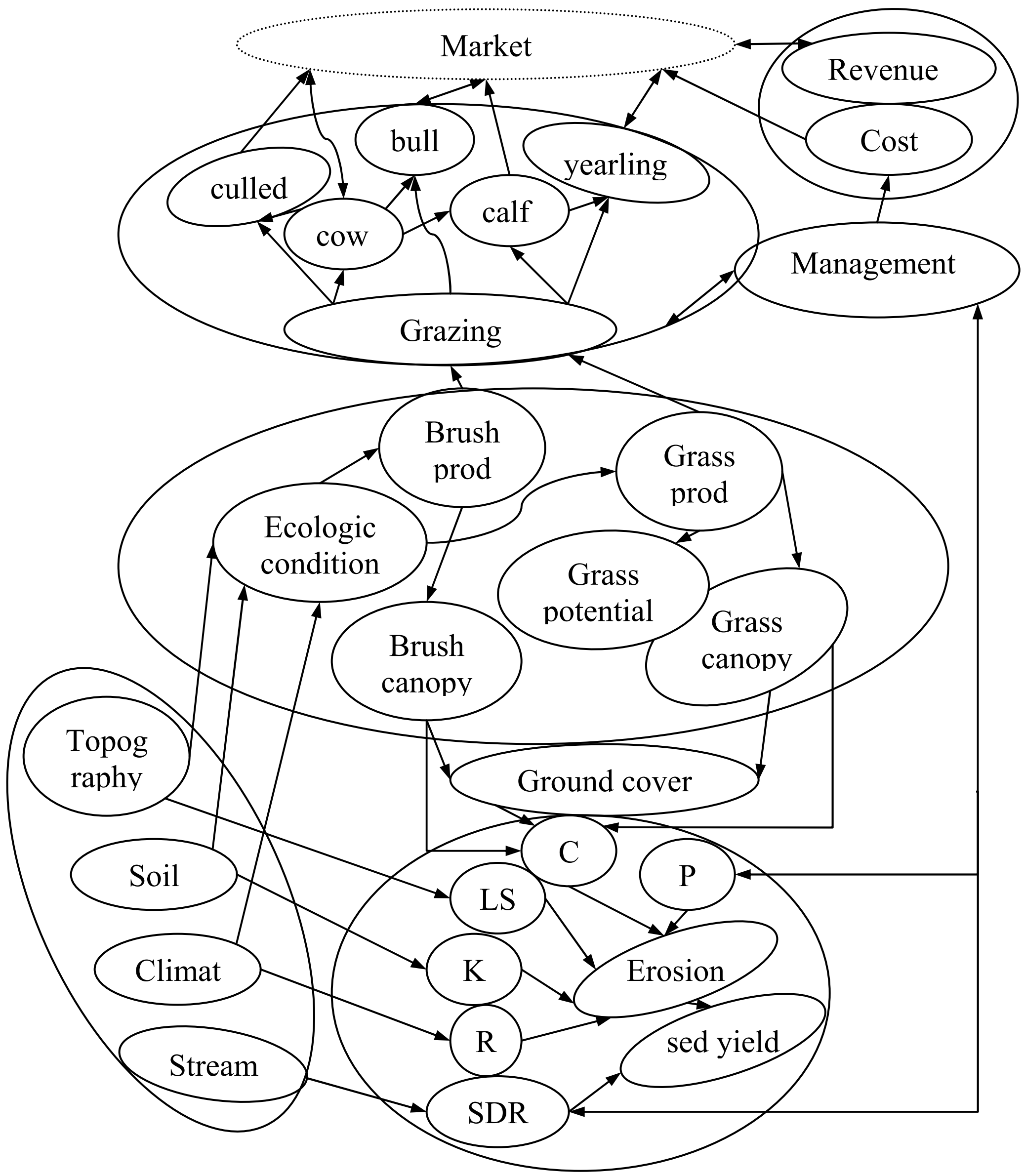


Figure A-1 Diagram of components, elements and their interactions in the models

APPENDIX B COMPUTE PROGRAM: SQL, AML & GAMS

SQL for Creating Database

```
CREATE TABLE OtherParameter (
   ParaName       varchar2(40)  PRIMARY KEY,
   Unit           varchar2(80),
   pvalue         number(20,10)
);
CREATE TABLE Watershed (
   WSID           varchar2(20)  PRIMARY KEY,
   WSName         varchar2(60)  NOT NULL,
   RanchSize      number(16,4)  NOT NULL,
   R_dry          number (5,2),
   R_normal       number (5,2),
   R_wet          number (5,2)
);
CREATE TABLE UserInfo (
   UserID         varchar2(20)  PRIMARY KEY,
   pin            varchar2(20)  NOT NULL,
   Name           varchar2(30)  NOT NULL,
   Type           varchar2(20),
   Email          varchar2(50)  NOT NULL,
   Address        varchar2(50),
   Affliction    varchar2(100),
   RegiDate       date DEFAULT  sysdate,
   Phone          varchar2(20)
);
CREATE TABLE PriceItem (
   PName          varchar2(35)  PRIMARY KEY,
   PUnit          varchar2(150) NOT NULL,
   po1            varchar2(1),
   po2            varchar2(1)
);
CREATE TABLE PriceSce (
   UserID         varchar2(20)  REFERENCES UserInfo,
   PSName         varchar2(20),
   PName          varchar2(35)  REFERENCES PriceItem,
   Amount         number(16, 4) NOT NULL,
   PSource        varchar(60),
   CONSTRAINT pricesce_pk PRIMARY KEY (UserID, PSName, PName)
);
CREATE TABLE EcoSite (
   EID            varchar2(20)  PRIMARY KEY,
   EcoName        varchar2(100),
   pro_wet        number(6,0),
   pro_normal     number(6,0),
   pro_dry        number(6,0),
   GrassPercent   number(5,4),
   brush_grazable number(4,3),
   soil_depth     varchar2(1),
   Con_good       number(4,3),
   Con_fair       number(4,3),
   Con_poor       number(4,3)
);
```

```
CREATE TABLE WS_EcoSite(
   WS             varchar2(20)  REFERENCES Watershed,
   EID            varchar2(20),
   ESID           varchar2(20)  REFERENCES EcoSite,
   CONSTRAINT ws_ecosite_pk PRIMARY KEY (WS, EID, ESID)
);
CREATE TABLE LayerName(
   layercode      number(10,0)  PRIMARY KEY
   WSID           varchar2(20)  REFERENCES Watershed,
   UserID         varchar2(20)  REFERENCES UserInfo,
   layertype      varchar2(20),
   layername      varchar2(20),
);
CREATE TABLE Pasture (
   WSID           varchar2(20)  REFERENCES Watershed,
   UserID         varchar2(20)  REFERENCES UserInfo,
   PPName         varchar2(20),
   PaName         varchar2(20),
   newfence       number(10,5),
   CONSTRAINT  pasture_pk PRIMARY KEY (WSID, UserID, PPName, PaName)
);
CREATE TABLE PastureSce (
   WSID           varchar2(20)  REFERENCES Watershed,
   UserID         varchar2(20)  REFERENCES UserInfo,
   PPName         varchar2(20),
   PaSName        varchar2(20),
   PaName         varchar2(20),
   Used           varchar2(1),
   CONSTRAINT pasturesce_pk PRIMARY KEY (WSID, UserID, PPName, PaSName,
PaName)
);
CREATE TABLE WaterPoint (
   WSID           varchar2(20)  REFERENCES Watershed,
   UserID         varchar2(20)  REFERENCES UserInfo,
   WPName         varchar2(20),
   WPID           varchar2(20),
   CONSTRAINT  wp_pk PRIMARY KEY (WSID, UserID, WPName, WPID)
);
CREATE TABLE Pond (
   WSID           varchar2(20)  REFERENCES Watershed,
   UserID         varchar2(20)  REFERENCES UserInfo,
   PLID           varchar2(20),
   PoID           varchar2(20),
   PoNAME         varchar2(20),
   Capacity       number(12,0),
   SDR            number(5,4),
   CONSTRAINT  pond_pk PRIMARY KEY (WSID, UserID, PLID, PoID)
);
CREATE TABLE PondSce (
   WSID           varchar2(20)  REFERENCES Watershed,
   UserID         varchar2(20)  REFERENCES UserInfo,
   PLID           varchar2(20),
   PoSName        varchar2(20),
   PoID           varchar2(20),
   built          varchar2(1),
   CONSTRAINT  wp_pk PRIMARY KEY (WSID, UserID, PLID, PoSName, PoID)
);
CREATE TABLE SensitiveItem(
   ItemName       varchar2(25)  PRIMARY KEY,
   MySource       varchar2(40),
   MyValue        varchar(10)
```

```
);
CREATE TABLE ManageSce (
   WSID           varchar2(20)  REFERENCES Watershed,
   UserID         varchar2(20)  REFERENCES UserInfo,
   MID            varchar2(20),
   PSName         varchar2(20),
   PPName         varchar2(20),
   PaSName        varchar2(20),
   WPName         varchar2(20),
   PLID           varchar2(20),
   PoSName        varchar2(20),
   years          varchar2(2),
   EcoCondition   varchar2(10),
   SedObj         number(10,2),
   Plant          varchar2(1),
   Animal         varchar2(1),
   CS_Pond        number(6,4),
   CS_Fence       number(6,4),
   CS_WP          number(6,4),
   MComment       varchar2(200),
   CONSTRAINT managesce_pk PRIMARY KEY (WSID, UserID, MID)
 );
CREATE TABLE BasicUnit1(
   WSID           varchar2(20)  REFERENCES Watershed,
   UserID         varchar2(20)  REFERENCES UserInfo,
   EID            varchar2(20),
   PPName         varchar2(20),
   WPName         varchar2(20),
   PaName         varchar2(20),
   RockCover      number(8, 4),
   KLS            number(8, 4),
   Adj1           number(8, 4),
   Adj2           number(8, 4),
   CONSTRAINT  bu_pk PRIMARY KEY (WSID, UserID, EID, PPName, WPname,
PaName)
);
CREATE TABLE BasicUnit2(
   WSID           varchar2(20)  REFERENCES Watershed,
   UserID         varchar2(20)  REFERENCES UserInfo,
   EID            varchar2(20),
   PPName         varchar2(20),
   WPName         varchar2(20),
   PaName         varchar2(20),
   PLID           varchar2(20),
   PoID           varchar2(20),
   Area           number(10,4),
   SedDR          number(8, 4),
   CONSTRAINT   bu1_pk PRIMARY KEY (WSID, UserID, EID, PPName, WPname,
PaName, PLID, PoID)
);
CREATE TABLE OptSummary (
   WSID           varchar2(20)   REFERENCES Watershed,
   UserID         varchar2(20)   REFERENCES UserInfo,
   MID            varchar2(20),
   year           number(2,0),
   climate        varchar2(10),
   Income         number(20,10),
   t_cost         number(20,10),
   cost_bmp       number(20,10),
   Herd           number(20,10),
   cow_sold       number(6,2),
```

```
   bull_sold      number(6,2),
   steer_sold     number(6,2),
   heifer_sold    number(6,2),
   yearling       number(6,2),
   SedYield       number (16,4),
   Erosion        number (16,4),
   CONSTRAINT  optsummary_pk PRIMARY KEY (WSID, UserID, MID, year)
);
CREATE TABLE OptDetail(
   WSID           varchar2(20)  REFERENCES Watershed,
   UserID         varchar2(20)  REFERENCES UserInfo,
   MID            varchar2(20),
   EID            varchar2(20),
   PPNAME         varchar2(20),
   PaNAME         varchar2(20),
   year           number(2,0),
   Erosion        number(20,10),
   pro_grass      number(20,10),
   pro_brush      number(20,10),
   grazed_grass   number(20,10),
   grazed_brush   number(20,10),
   canopycover    number(20,10),
   groudcover     number(20,10),
   CONSTRAINT  optdetail_pk PRIMARY KEY (WSID, UserID, MID, PPName,
year)
 );

CREATE TABLE OptSensitive (
   WSID           varchar2(20)  REFERENCES Watershed,
   UserID         varchar2(20)  REFERENCES UserInfo,
   MID            varchar2(20),
   SenID          varchar2(20)  REFERENCES SensitiveItem,
   climate        varchar2(10),
   ItemValue      number(10,4),
   MValue         number(10, 4),
   CONSTRAINT optsensitive_pk PRIMARY KEY (WSID, UserID, MID, SenID,
ItemValue)
);
CREATE TABLE AbateCost(
   WSID           varchar2(20)   REFERENCES Watershed,
   UserID         varchar2(20)   REFERENCES UserInfo,
   MID            varchar2(20),
   climate        varchar2(10),
   SedYield       number(20,6),
   Profit         number(20,6),
   CONSTRAINT optsensitive_pk PRIMARY KEY (WSID, UserID, MID, SedYield)
);
```

GAMS code for the Static Model

```
SETS
  i       ecological site index
  j       pasture index
  build   built pond index

********************************
* Parameter section
* Parameters will be created on the fly.
********************************

POSITIVE VARIABLES
  grazed_forage      total forage grazed in a watershed (lb)
  biomass_g(i,j)     old standing grass biomass (lb/acre)
  biomass_b(i,j)     old standing brush biomass (lb/acre)
  pro_b(i,j)         brush production (lb/acre)
  pro_g(i,j)         grass production (lb/acre)
  gra_b(i,j)         brush production grazed (lb/acre)
  gra_g(i,j)         grass production grazed (lb/acre)
  u_g(i,j)           grass utilization (%)
  canopy_w(i,j)      canopy in weight (lb/acre)
  canopy_p(i,j)      canopy in percent (%)
  gc_w(i,j)          biomass ground cover in weight (lb/acre)
  gc_p1(i,j)         biomass ground cover (%)
  gc_p2(i,j)         total ground cover (%)
  c(i,j)             RUSLE2 C factor
  ero(i,j)           erosion rate of each basic unit (tons/acre)
  pot_soil(i,j)      the soil productivity index
  t_ero              total erosion of a watershed (tons/year)
  sed                sediment yield of a watershed at outlet (tons/ year)
  pond_life(build)   the time to fill a pond (years)
  herd_size          the number of cow/calf pairs
  income             the total revenue
  cost               the total cost
  cost_BMP           cost related with BMP activities
  hay_bought         cost to buy extra hay for livestock
  plu(i,j)           PLU factor in RUSLE2 C factor
  cc(i,j)            CC factor in RUSLE2 C factor
  sc(i,j)            SC factor in RUSLE2 C factor
  sr(i,j)            SR factor in RUSLE2 C factor
  rs(i,j)            RS factor in RUSLE2 C factor;
VARIABLES
  profit             profit of a representative ranch;
EQUATIONS

*********************************
* production
*********************************

* production depends on the climate, ecological condition and brush/grass
* percentage and may include feedback of grazing
  pro_b_e(i,j)..      pro_b(i,j) =e= sum(climate, forage_pro(i,climate)
                        * my_climate(climate))*(1 - grass_percent(i))
                        * sum(l, forage_condition(i,l) * my_condition(l));
 * Type 1   grazing impacts is 0
  pro_g_e(i,j)..      pro_g(i,j) =e= sum(climate, forage_pro(i,climate)
                        * my_climate(climate)) * grass_percent(i)
                        * sum(l, forage_condition(i,l) * my_condition(l))
                        * pot_soil(i,j);
*  Type 2   grazing impacts is invert 'U'
  pro_g_e(i,j)..      pro_g(i,j) =e= sum(climate, forage_pro(i,climate)
                        * my_climate(climate)) * grass_percent(i)
```

```
                        * sum(l, forage_condition(i,l) * my_condition(l))
                        * pot_soil(i,j) * (gra_pro_a * u_g(i,j) * u_g(i,j)
                        + gra_pro_b * u_g(i,j) + gra_pro_c);

**********************************
* grazing
**********************************

*  ungrazed pastures set as zero
  ungrazed_g(ug,i)..  gra_g(i,ug) =l= 0;
  ungrazed_b(ug,i)..  gra_b(i,ug) =l= 0;

  util_g(i, j)..     u_g(i, j) * pro_g(i, j) =e= gra_g(i, j) ;
*********************
* Type 1  grazing based on range map
*         forage utilization is adjusted with slope and distance to water
  gra_con_b(i,j)..   gra_b(i,j) =l= util_brush * pro_b(i,j) * slope_adj(i,j)
                                  * brush_grazable_percent(i);
  gra_con_g(i,j)..   gra_g(i,j) =l= util_grass * pro_g(i,j) * slope_adj(i,j);

* Type 2  grazing based on regression
*         forage utilization is adjusted by regression relationship
  gra_con_b(i,j)..   gra_b(i,j) =l= util_brush * pro_b(i,j) * u_g(i,j)
                                  / util_grass * brush_grazable_percent(i);
  gra_con_g(i,j)..   gra_g(i,j) =l= util_grass * pro_g(i,j);
  gra_cost(i,j)..    reg_adj(i,j) =l= log(1 - u_g(i,j));

*******************************
* Grazing equilibrium
*******************************

  total forage..     grazed_forage =e= sum((i,j,k), (gra_b(i,j) + gra_g(i,j))
                                     * area(i,j,k)) + hay_bought;
  foragereq..   grazed_forage =g= (herd_size * cow_aum_req * (1 + cow_cull_ratio)
                                + herd_size / 2 * keep_ratio * yearling_aum_req
                                + herd_size / bull_ratio * bull_aum_req
                                * (1 + bull_cull_ratio)
                                + horse_num * horse_aum_req * ranch_size
                                / standard_ranch_size) * 12 * aum_weight_ratio;

***********************************
* biomass
***********************************
*  assumes brush biomass reach equilibrium of 20 years growth.
  biomass_b_e(i,j).. biomass_b(i,j) =e= (pro_b(i,j) - gra_b(i,j)) * 20 ;
  biomass_g_e(i,j).. biomass_g(i,j) =e= (pro_g(i,j) - gra_g(i,j))
                                      / decay_ratio_g ;
*  total canopy cover of grass and biomass
  canopy_w_e(i,j)..  canopy_w(i,j) =e= biomass_b(i,j) + biomass_g(i,j);
  canopy_p_e(i,j)..  canopy_p(i,j) =e= cb_w_p2 * Power(canopy_w(i,j), 2)
                                     + canopy_w(i,j) * cb_w_p1;
*  ground cover is composed of rock fragments, grass and brush litter cover.
  gc_w_e(i,j)..      gc_w(i,j)  =e= (pro_g(i,j) - gra_g(i,j) + (pro_b(i,j)
                                - gra_b(i,j)) * decay_ratio_b) / decay_ratio_gc;
  gc_p1_e(i,j)..     gc_p1(i,j) =e= power(gc_w(i,j), 2) * gc_w_p2 + gc_w(i,j)
                                  * gc_w_p1;
  gc_p2_e(i,j)..     gc_p2(i,j) =e= ero_pav(i,j)/100 + gc_p1(i,j) - ero_pav(i,j)
                                  / 100 * gc_p1(i,j)+ pro_basal_area
                                  * (pro_g(i,j) - gra_g(i,j));
* C subfactor from RUSLE2 for rangeland
  RS_e(i,j)..        rs(i,j)  =e= (biomass_b(i,j) + biomass_g(i,j)) * 0.8922
                                * (0.38 * 2.28 * grass_percent(i) + 0.56 * 1.23
                                * (1 - grass_percent(i)))/100;
  PLU_e(i,j)..       plu(i,j) =e= 0.45 * exp(-0.012 * rs(i,j));
* vegetation height is 0.,2 meter for grass and 0.5 for brush.
  CC_e(i,j)..        cc(i,j)  =e= 1 - canopy_p(i,j)* exp(-0.34 * (0.15
                                + 0.3 * grass_percent(i)));
  SC_e(i,j)..        sc(i,j)  =e= exp(-4.0 * gc_p2(i,j));
```

```
* set random roughness as constant, 20 mm.
  SR_e(i,j)..        sr(i,j)  =e= exp(-0.026 * (20 - 6) * (1
                              - exp(-0.035 * rs(i,j))));

****************************************
* erosion
****************************************

  rusle2_c(i,j)..    c(i,j) =e= plu(i,j) * cc(i,j) * sc(i,j) * sr(i,j);
*  Erosion is calculated with the RUSLE2.
  erosion(i,j)..     ero(i,j) =e= sum(climate, USLE_R(climate)
                              * my_climate(climate)) * KLS(i,j) * c(i,j);
*  Total erosion.
  teros..            t_ero =e= sum((i,j,k), ero(i,j) * area (i,j,k));
  pond_life_e(build).. pond_capacity(build) * sed_density =g= pond_life(build)
                       * sum((i,j),  ero(i,j) * area (i,j,build)
                       * sed_ratio(i,j,build) / pond_SDR(build));
* soil productivity is adjusted by soil loss for shallow soil
  ero_pot1(i,j)..    pot_soil(i,j) =e= 1 - ero_pot * ero(i,j)
                                  * (1 - soil_depth(i)) + natural rate ;
* sediment yield
  eyelid..         sed =e= sum((i,j,k),  ero(i,j) * area (i,j,k)
                         * sed_ratio(i,j,k)) - sum((i,j,build), ero(i,j)
                         * area (i,j,build) * sed_ratio(i,j,build));
*  Sediment control constrain.
  sedyield_con..     sed =l= sed_obj;

***************************************
* economic
***************************************

* Profits are calculated as the earnings from heifers, steers, and cull cows
* less variable and constant costs.
  tcosts..    cost =e= fixed_cost * r / 0.08 * ranch_size / standard_ranch_size
                     + r * herd_size * (price_cow - price_cow_cull * (1 - r))
                     * weight_cow + r * herd_size * (price_bull - price_bull_cull
                     * (1 - r)) * weight_bull / bull_ratio
                     + r * herd_size * (price_yearling - price_cow_cull *(1 - r))
                     * weight_yearling * calf_ratio * keep_ratio
                     + herd_size * (feed_cost + other_cost) * ( 1 + r )
                     * (1 - management_cost_ratio) + hay_bought * price_hay
                     * (1 + r) * (1 - management_cost_ratio)
                     + management_cost_ratio * income;
  profits..   profit =e= income - cost - cost_BMP;
  incomes..   income =e= 0.5 * calf_ratio * herd_size * price_heifer_calf
                       * (1 - keep_ratio) * weight_calf_heifer
                       + 0.5 * calf_ratio * herd_size * price_steer_calf
                       * weight_calf_steer + herd_size * cow_cull_ratio
                       * weight_cow * price_cow_cull + herd_size / bull_ratio
                       * bull_cull_ratio * weight_bull * price_bull_cull;
  cost_BMPs.. cost_BMP =e= fence_added * cost_fence * (1 - cost_sharing_fence)
                         + maintenance_fence * fence_added * (1 + r)
                         + waterpoint_added * cost_waterpoint
                         * (1 - cost_sharing_waterpoint )
                         + maintenance_waterpoint * waterpoint_added * (1 + r)
                         + pond_added * cost_pond * (1 - cost_sharing_pond)
                         + sum(build, pond_capacity(build) * cost_dredge_pond
                         * r / (1 + r + (1 + r) * log(1 + r) * pond_life(build)
                         +  power(1 + r, 2) * power(log(1 + r), 2)
                         * power(pond_life(build), 2) / 2 - 1));
model social_opt / all /;
solve social_opt maximizing profit using NLP;

*********************************
* Model procedure and output is added according model type on the fly
*********************************
```

GAMS Code for the Dynamic Model

```
SETS
i       ecological site index
j       pasture index
build   built pond index
s       season index
t       planning year index with 0
tt      subset of planning year without 0

********************************
* Parameter section
* Parameters will be created on the fly.
********************************

VARIABLES
  total_profit_NPV        NPV profit of planning year.
  profit(t)               profit of year t;

POSITIVE VARIABLES
  pro_b(i,j,t,s)          brush production (lb/acre)
  pro_g(i,j,t,s)          grass production (lb/acre)
  gra_g_canopy(i,j,t,s)   old grass biomass grazed (lb/acre)
  gra_b_pro(i,j,t,s)      brush production grazed (lb/acre)
  gra_g_pro(i,j,t,s)      grass production grazed (lb/acre)
  dry_matter(t,s)         total forage grazed (lb/acre)
  hay(t,s)                hay bought for extra feed cost (lb)Sets
  gc_w(i,j,t,s)           ground cover in weight (lb/acre)
  gc_p1(i,j,t)            ground cover of dead biomass (%)
  gc_p2(i,j,t)            total ground cover including basal and rock (%)
  canopy_b(i,j,t,s)       standing brush biomass (lb/acre)
  canopy_g(i,j,t,s)       standing grass biomass (lb/acre)
  canopy_w(i,j,t)         total standing biomass (lb/acre)
  canopy_p(i,j,t)         canopy cover (%)
  plu(i,j,tt)             PLU factor in C
  cc(i,j,tt)              CC factor in C
  sc(i,j,tt)              SC factor in C
  sr(i,j,tt)              SR factor in C
  rs(i,j,tt)              RS factor in C
  C(i,j,t)                RUSLE2 C factor
  pot_soil(i,j,t)         the soil productivity index
  ero(i,j,t)              erosion rate of each basic unit (tons/acre)
  sed_yield(t)            sediment yield at a watershed outlet(tons/year)
  pond_life(build, t)     the time of a pond is full (years)
  herd_size(t)            the number of cow/calf pair
  cow_cull(t)             the number of cow culled (heads)
  cow_sold(t)             the number of cow sold (heads)
  yearling(t)             the number of yearling (heads)
  yearling_sold(t)        the number of yearling sold (heads)
  cow_bought(t)           the number of cow bought (heads)
  calf(t)                 the number of calves (heads)
  calf_heifer_sold(tt)    the number of heifer calf sold (heads)
  bull(t)                 the number of bull (heads)
  bull_cull(t)            the number of bull culled (heads)
  bull_sold(tt)           the number of bull sold (heads)
  bull_bought(tt)         the number of bull bought (heads)
  revenue(t)              the total revenue in year ($)
  cost(t)                 the total cost in year ($)
  capital_loss(tt)        total capital loss by herd adjustment ($)
```

```
  cost_BMP(t)             the total cost in BMP activities ($) ;

EQUATIONS
**********************************
* set potential soil at beginning as 1.0 and make adjustments
  pot_soil_e0(i,j)..    pot_soil(i,j,'0') =e= 1.0 ;
  pot_soil_e(i,j,t+1).. pot_soil(i,j,t+1) =e= pot_soil(i,j,t)
                                 + natural_rate - ero_pot * ero(i,j,t+1)
                                 * (1 - soil_depth(i));
**********************************
* plant growth and biomass change
**********************************

  prod_b(i,j,tt,s)..    pro_b(i,j,tt,s) =l= brush_season(s)
                             * sum(climate, forage_pro(i, climate)
                             * my_climate(tt,climate))
                             * sum(l, forage_condition(i,l)
                             * my_condition(l))
                             * (1 - grass_percent(i));

* Type 1 production does not adjust with utilization
  prod_g(i,j,tt,s)..    pro_g(i,j,tt,s) =l= grass_season(s)
                             * sum(climate, forage_pro(i, climate)
                             * my_climate(tt,climate))
                             * sum(l, forage_condition(i, l)
                             * my_condition(l))
                             * grass_percent(i) * pot_soil(i,j,tt);

*  Type 2   grazing impacts is invert 'U'
  prod_g(i,j,tt,s)..    pro_g(i,j,tt,s) =l= grass_season(s)
                            * sum(climate, forage_pro(i, climate)
                            * my_climate(tt,climate))
                            * sum(l, forage_condition(i, l)
                            * my_condition(l))
                            * grass_percent(i) * pot_soil(i,j,tt)
                            * (gra_pro_a * u_g(i,j,tt) * u_g(i,j,tt)
                            + gra_pro_b * u_g(i,j,tt) + gra_pro_c);
  pro_g_e(i,j)..        pro_g(i,j) =e= sum(climate, forage_pro(i,climate)
                             * my_climate(climate)) * grass_percent(i)
                        * sum(l, forage_condition(i,l) * my_condition(l))
                        * pot_soil(i,j)
***********************************
  canopy_b2(i,j,tt)..    canopy_b(i,j,tt,'1') =e= canopy_b(i,j,tt--1,'4')
                                  * 0.95 + (1 - decay_b('1'))
                                  * (pro_b(i,j,tt,'1')
                                  - gra_b_pro(i,j,tt,'1'));
  canopy_b1(i,j,tt,s+1)..canopy_b(i,j,tt,s+1) =e= canopy_b(i,j,tt,s)
                                 * 0.95 + (1 - decay_b(s+1))
                                 * (pro_b(i,j,tt,s+1)
                                 - gra_b_pro(i,j,tt,s+1));
  canopy_g2(i,j,tt)..    canopy_g(i,j,tt,'1') =e= canopy_g(i,j,tt--1,'4')
                                 * (1 - decay_g('1'))
                                 - gra_g_canopy(i,j,tt,'1')
                                 + pro_g(i,j,tt,'1')
                                 - gra_g_pro(i,j,tt,'1');
  canopy_g1(i,j,tt,s+1)..canopy_g(i,j,tt,s+1) =e= canopy_g(i,j,tt,s)
                                 * (1 - decay_g(s+1)) + pro_g(i,j,tt,s+1)
                                 - gra_g_pro(i,j,tt,s+1)
                                 - gra_g_canopy(i,j,tt,s+1) ;

***********************************
```

```
*grazing
***********************************

  gra_util(i,j,tt)..     u_g(i,j,tt) =e= sum(s, gra_g_pro(i,j,tt,s))
                                 / sum(s, pro_g(i,j,tt,s));
  gra_util_c(i,j,tt)..   u_g(i,j,tt) =e= util_g_max;

* grazing distribution

* Type 1  range map
  gra_b_e(i,j,tt,s)..    gra_b_pro(i,j,tt,s) =l= util_b_max
                                 * pro_b(i,j,tt,s) * slope_adj(i,j)
                                 * brush_grazable_percent(i);
  gra_g_e(i,j,tt,s)..    gra_g_pro(i,j,tt,s) =l= util_g_max
                                 * pro_g(i,j,tt,s) * slope_adj(i,j);
  gra_c1_e(i,j,tt)..     gra_g_canopy(i,j,tt,'1') =l= util_c_max
                                 * canopy_g(i,j,tt--1,'4')
                                 * slope_adj(i,j);
  gra_c2_e(i,j,tt,s+1).. gra_g_canopy(i,j,tt,s+1) =l= util_c_max

* ungrazed area set grazing as zero
  ungraze_b_e(i,ug,tt,s).. gra_b_pro(i,ug,tt,s)    =l= 0;
  ungraze_g_e(i,ug,tt,s).. gra_g_pro(i,ug,tt,s)    =l= 0;
  ungraze_c_e(i,ug,tt,s).. gra_g_canopy(i,ug,tt,s) =l= 0;

* grazing equilibrium
  dry_matter_e(tt,s)..   dry_matter(tt,s) =e= sum((i,j,k),
                                 ( gra_b_pro(i,j,tt,s)
                                  + gra_g_pro(i,j,tt,s)
                                  + gra_g_canopy(i,j,tt,s))
                                  * area(i,j,k));
  total_aum_e(tt,s)..    dry_matter(tt,s) + hay(tt, s) =g= (cow_aum_req
                                * ( herd_size(tt) + cow_cull(tt))
                                + yearling_aum_req * yearling(tt)
                                + bull_aum_req * ( bull(tt)
                                + bull_cull(tt))
                                + horse_num * horse_aum_req
                                * ranch_size / standard_ranch_size)
                                * aum_weight_ratio * 3;

***********************************
* Erosion
***********************************

* only consider erosion by summer storm
  gc_w1_e(i,j,tt)..    gc_w(i,j,tt,'1') =e= gc_w(i,j,tt--1,'4')
                           * (1 - gc_decay('1'))
                           + canopy_b(i,j,tt--1,'4')
                           * decay_b('1') + canopy_g(i,j,tt--1,'4')
                           * decay_g('1') ;
  gc_w_e(i,j,tt,s+1).. gc_w(i,j,tt,s+1) =e= gc_w(i,j,tt,s)
                           * (1 - gc_decay(s+1))
                           + canopy_b(i,j,tt,s) * decay_b(s+1)
                           + canopy_g(i,j,tt,s) * decay_g(s+1);
  gc_p_e(i,j,tt)..     gc_p1(i,j,tt) =e= power((0.66 * gc_w(i,j,tt,'3')
                           + 0.33 * gc_w(i,j,tt,'4')), 2) * gc_w_p2
                           + (0.66 * gc_w(i,j,tt,'3')
                           + 0.33 * gc_w(i,j,tt,'4')) * gc_w_p1;
  gc_p2_e(i,j,tt)..    gc_p2(i,j,tt) =e= gc_p1(i,j,tt)+ero_pav(i,j)/100
                           * (1 - gc_p1(i,j,tt)) + pro_basal_area
                           * sum(s, pro_g(i,j,tt, s));
```

```
 canopy_w_e(i,j,tt).. canopy_w(i,j,tt) =e= 0.66 * canopy_b(i,j,tt,'3')
                          + 0.33 * canopy_b(i,j,tt,'4')
                          + 0.66 * canopy_g(i,j,tt,'3')
                          + 0.33 * canopy_g(i,j,tt,'4');
  canopy_p_e(i,j,tt).. canopy_p(i,j,tt) =e= cb_w_p2
                          * power(canopy_w(i,j,tt),2)
                          + canopy_w(i,j,tt) * cb_w_p1;

* RUSLE2  C subfactor
  RS_e(i,j,tt)..       rs(i,j,tt) =e= (canopy_b(i,j,tt,'3') * 2
                          + canopy_b(i,j,tt,'4') + gc_w(i,j,tt,'3') * 2
                          + gc_w(i,j,tt,'4')) / 3 * 0.8922 * (0.38*2.28
                          * grass_percent(i) + 0.56 * 1.23
                          * (1 - grass_percent(i)))/100 ;
  PLU_e(i,j,tt)..      plu(i,j,tt) =e= 0.45 * exp(-0.012 * rs(i,j,tt));
  CC_e(i,j,tt)..       cc(i,j,tt) =e= 1 - canopy_p(i,j,tt)
                          * exp(-0.34 * (0.15 + 0.3*grass_percent(i)));
  SC_e(i,j,tt)..       sc(i,j,tt) =e= exp(-4.0 * gc_p2(i,j,tt));

* set random roughness as constant 20 mm.
* TAYLOR approximation of exp() is used to simplify computation
  SR_e(i,j,tt)..       sr(i,j,tt) =e= exp(-0.026*14*0.035*rs(i,j,tt));
  usle_c(i,j,tt)..     C(i,j,tt) =e= plu(i,j,tt) * cc(i,j,tt)
                          *sc(i,j,tt) * sr(i,j,tt);
  erosion(i,j,tt)..    ero(i,j,tt) =e= sum(climate,my_climate(tt,climate)
                          * USLE_R(climate)) * KLS(i,j) * C(i,j,tt);

* sediment yield is erosion times SDR.
  sed_yield_e(tt)..    sed_yield(tt) =e= sum((i,j,k), ero(i,j,tt)
                          * area(i,j, k) * sed_ratio(i,j,k))
                          - sum((i,j,build), ero(i,j,tt)
                          * area(i,j, build) * sed_ratio(i,j,build));
* sediment yield constrains
  sed_control_e(tt)..  sed_yield(tt) =l= sum(climate,
                          my_climate(tt, climate)
                          * USLE_R(climate)) * sed_obj / USLE_R('2');
  pond_life_e(build, tt).. pond_capacity(build) * sed_density =g=
                          pond_life(build, tt) * sum((i,j), ero(i,j,tt)
                          * area(i,j,build) * sed_ratio(i,j,build)
                          / pond_sdr(build));

*********************************
*ranch operation: a typical cow-calf-yearling ranch
*********************************

  cow_cull_e(tt)..     cow_cull(tt) =e= cow_cull_ratio *(herd_size(tt--1)
                          * (1 - death_rate) - cow_sold(tt--1));
  cow_sold_c1(tt)..    cow_sold(tt) =l= herd_size(tt) * (1 - death_rate);
  cow_sold_c2(tt)..    cow_bought(tt) * cow_sold(tt--1) =l= 0 ;
  herd_size_e(tt)..    herd_size(tt) =e= herd_size(tt--1)
                          *(1-death_rate) - cow_cull(tt--1)
                          + cow_bought(tt) - cow_sold(tt--1)
                          + yearling(tt--1) - yearling_sold(tt--1);
  bull_0e(tt)..        bull_cull(tt) =e= bull(tt--1) * bull_cull_ratio;
  bull_1e(tt)..        bull(tt) =e= bull(tt--1) - bull_cull(tt)
                          - bull_sold(tt--1) + bull_bought(tt);
  bull_2e(tt)..        bull(tt) =e= herd_size(tt) / bull_ratio;
  bull_3e(tt)..        bull_sold(tt) =l= bull(tt);
  calf_e(tt)..         calf(tt) =e= herd_size(tt) * calf_ratio;
  calf_heifer_sold_e(tt).. calf_heifer_sold(tt) =l= calf(tt) / 2;
  yearling_e(tt)..         yearling(tt) =e= calf(tt--1) / 2
```

```
                         - calf_heifer_sold(tt--1);
  yearling_sold_c1(tt)..   yearling(tt--1) - yearling_sold(tt--1) =g=
                         cow_cull(tt);
  yearling_sold_c2(tt)..   cow_bought(tt) * yearling_sold(tt--1) =l= 0;

***********************************
* Economics
***********************************

  income_e(tt)..       revenue(tt) =e= calf(tt) * weight_calf_steer
                           * price_steer_calf / 2 + calf_heifer_sold(tt)
                           * weight_calf_heifer * price_heifer_calf
                           + yearling(tt) * weight_yearling
                           * price_yearling;
* capital loss to add cost if herd size is adjusted
  capital_loss_e(tt).. captial_loss(tt) =e= 0.5 * cow_sold(tt)
                           * weight_cow
                           * (price_cow - price_cow_cull)
                           + 0.5 * bull_sold(tt) * weight_bull
                           * (price_bull - price_bull_cull);
  cost_e(tt)..         cost(tt) =e=  fixed_cost * r / 0.08 * ranch_size
                           / standard_ranch_size + herd_size(tt)
                           * (feed_cost + other_cost) * (1 + r)
                           * (1 - management_cost_ratio)
                           + sum(s, hay(tt,s)) * price_hay * (1 + r)
                           * (1 - management_cost_ratio)
                           + r * herd_size(tt)
                           * (price_cow + (price_cow - price_cow_cull)
                           / (power((1 + r),5) - 1)) * weight_cow
                           + r * bull(tt) * (price_bull + (price_bull
                           - price_bull_cull) / (power((1+r), 4) - 1))
                           * weight_bull + r * yearling(tt)
                           * price_yearling * weight_yearling
                           + management_cost_ratio * revenue(tt);
  cost_BMP_e(tt)..     cost_BMP(tt) =e= (cost_fence * cost_sharing_fence
                           + maintenance_fence * (1 + r)) * fence_added
                           + (cost_waterpoint * cost_sharing_waterpoint
                           + maintenance_waterpoint * (1 + r))
                           * waterpoint_added
                           + pond_added * cost_pond * cost_sharing_pond
                           + sum(build, pond_capacity(build)
                           * cost_dredge_pond
                           * r / (1 + r + (1 + r) * log(1 + r)
                           * pond_life(build,tt) + power(1 + r, 2)
                           * power(log(1 + r), 2)
                           * power(pond_life(build,tt), 2) / 2 - 1));

*********************************
* objective function
*********************************
  profit_e(tt)..       profit(tt) =e= revenue(tt) - cost(tt)
                           - capital_loss(tt) - cost_BMP(tt);
  profits_e..          total_profit_NPV =e= sum(tt, profit(tt)
                           / power((1+r), ord(tt)));
MODEL  onecase / all / ;
OPTION NLP = CONOPT3;
SOLVE  onecase using nlp maximizing total_profit_NPV;

******************************
* Model procedure and output is added according model type on the fly
******************************
```

AML Code to Create a New Pond Layer

```
/* delete existing layers if existed
&if [exists %layer%1 -POINT] &then; kill %layer%1 all
&if [exists %layer%2 -POINT] &then; kill %layer%2 all
&if [exists %layer%  -POINT] &then; kill %layer%  all
&if [exists %layer%g -GRID]  &then; kill %layer%g all
&if [exists %layer%ws -GRID] &then;  kill %layer%ws all
&if [exists %layer%.shp -file]
&then &sv ee = type [delete %layer%.shp -file]
&if [exists %layer%.shx -file]
&then &sv ee = type [delete %layer%.shx -file]
&if [exists %layer%.dbf -file]
&then &sv ee = type [delete %layer%.dbf -file]
&if [exists %layer%ws.shp -file]
&then &sv ee = type [delete %layer%ws.shp -file]
&if [exists %layer%ws.shx -file]
&then &sv ee = type [delete %layer%ws.shx -file]
&if [exists %layer%ws.dbf -file]
&then &sv ee = type [delete %layer%ws.dbf -file]
&if [exists %layer%.out -file]
&then &sv ee = type [delete %layer%.out -file]

/* create a coverage from user input files
tables
select ponds.pat
unload %input% number x_coord y_coord
quit

/* first create a point coverage
generate %layer%1
copytics boundary
input %input%
points
quit
build %layer%1 point

/* find the nearest point to potential pond points
near %layer%1 pond_pot line 500 %layer%2 location
build %layer%2 point
/* output corrected point
tables
select %layer%2.pat
/* remove the points that are too far away from stream
reselect x-coord > 0
unload %layer%.txt %layer%2-ID x-coord y-coord delimited init
quit

/* add an END to the file to generate a new file
&s fileunit = [open %layer%.txt openstatus -append]
&setvar eof = END
&sv ss = [write %fileunit% %eof%]
&sv ss = [close %fileunit%]

/* create new pond coverage
generate %layer%
copytics boundary
input %layer%.txt
points
```

```
quit
build %layer% point

/* create shape file
arcshape %layer% points %layer% define
%layer%-id pond_id 10 N 0
end

/* create grid layer for pond from coverage
grid
%layer%g = pointgrid(%layer%, %layer%-id, #,#, 10, nodata)

/* create the subwatersheds for new ponds
%layer%ws = watershed(flowdir, %layer%g)
/* create new shape files for new subwatersheds
%layer%ws = gridshape(%layer%ws)
/* sample data from layer to be read back to the database
%layer%.out = sample(%layer%g, sdr, pond_capa)
quit
quit
```

AML Code to Create New Water Point Layer

```
/* test and kill existing coverage
&if [exists %layer% -point] &then; kill %layer% all
&if [exists %layer%.shp -file]
&then &sv ee = type [delete %layer%.shp -file]
&if [exists %layer%.shx -file]
&then &sv ee = type [delete %layer%.shx -file]
&if [exists %layer%.dbf -file]
&then &sv ee = type [delete %layer%.dbf -file]
&if [exists %layer%.shp.xml -file]
&then &sv ee = type [delete %layer%.shp.xml. -file]

/* create new coverage from user input files
tables
select wp.pat
unload %input% WP_ID X-COORD Y-COORD
quit

/* add END to file to generate a new file
&s fileunit = [open %input% openstatus -append]
&setvar eof = END
&sv ss = [write %fileunit% %eof%]
&sv ss = [close %fileunit%]

/* Create new water point layer
generate %layer%
copytics boundary
input %input%
points
quit

build %layer% point
arcshape %layer% points %layer%

/* output the data from new water point layer
tables
select %layer%.pat
unload %layer%.out %layer%-ID init
quit
&if [exists %layer% -point] &then; kill %layer% all
quit
```

AML for Creating New Fence Layer and Pasture

```
/* delete layers if existed
&if [exists %layer%1 -LINE]    &then; kill %layer%1 all
&if [exists %layer%1 -POLYGON] &then; kill %layer%1 all
&if [exists %layer%  -POLYGON] &then; kill %layer%  all
&if [exists %layer%  -LINE]    &then; kill %layer%  all
&if [exists %layer%.shp -file]
&then &sv ee = type [delete %layer%.shp -file]
&if [exists %layer%.shx -file]
&then &sv ee = type [delete %layer%.shx -file]
&if [exists %layer%.dbf -file]
&then &sv ee = type [delete %layer%.dbf -file]
/* layer_1  create arc form input x y

/* create new fence coverage
generate %layer%1
copytics boundary
input %input%
lines
quit
build %layer%1 lines

/* append old water point
append %layer%
fence
%layer%1
end
clean %layer% %layer% 500 200 poly
build %layer% poly

/* output shape file
arcshape %layer% polys %layer% define
%layer%# past-id 10 N 0
end

/* output layer data to be read back to database
tables
select %layer%.pat
unload %layer%.out %layer%# init
quit
quit
```

AML for Creating New Basic Unit Layer

```
/* delete existing layers and files
&if [exists %layer%1 -LINE]     &then; kill %layer%1 all
&if [exists %layer%1 -POLYGON]  &then; kill %layer%1 all
&if [exists %layer%mask -POINT] &then; kill %layer%mask all
&if [exists %layer%wp -GRID]    &then; kill %layer%wp all
&if [exists %fence%ag -GRID]    &then; kill %fence%ag all
&if [exists %fence%cs -GRID]    &then; kill %fence%cs all
&if [exists %layer%dist  -GRID] &then; kill %layer%dist all
&if [exists %layer%dis1  -GRID] &then; kill %layer%dis1 all
&if [exists %layer%dis2  -GRID] &then; kill %layer%dis2 all
&if [exists %layer%s1   -GRID]  &then; kill %layer%s1 all
&if [exists %layer%reg1 -GRID]  &then; kill %layer%reg1 all
&if [exists %fence%g    -GRID]  &then; kill %fence%g all
&if [exists %layer%bu1  -GRID]  &then; kill %layer%bu1 all
&if [exists %layer%bu2  -GRID]  &then; kill %layer%bu2 all
&if [exists %layer%rock -GRID]  &then; kill %layer%rock all
&if [exists %layer%kls  -GRID]  &then; kill %layer%kls all
&if [exists %layer%sdr  -GRID]  &then; kill %layer%sdr all
&if [exists %layer%adj1 -GRID]  &then; kill %layer%adj1 all
&if [exists %layer%adj2 -GRID]  &then; kill %layer%adj2 all
&if [exists %layer%.shp -file]
&then &sv ee = type [delete %layer%.shp -file]
&if [exists %layer%.shx -file]
&then &sv ee = type [delete %layer%.shx -file]
&if [exists %layer%.dbf -file]
&then &sv ee = type [delete %layer%.dbf -file]
&if [exists %layer%.txt -file]
&then &sv ee = type [delete %layer%.txt -file]
&if [exists %layer%bu1p -POLYGON]
&then; kill %layer%bu1p all
&if [exists %layer%mask -POINT]
&then; kill %layer%mask all
&if [exists %layer%mg -GRID]   &then; kill %layer%mg all
&if [exists %layer%.out -file]
&then &sv ee = type [delete %layer%.out -file]

grid
/* create grid layer of water point
%layer%wp = shapegrid(%wp%.shp, %wp%_ID, 10)
/* create the distance to water point in each pasture
%fence%ag = linegrid(%fence%,#,#,#, 10, zero)
%fence%cs = con(%fence%ag > 0, 300, 1)
%layer%dist = costdistance(%layer%wp, %fence%cs, #, #, #, # )
/* adjust factor according to distance to water
/* 1 mile 1; 1-2 0.5; >2 mile 0.
%layer%dis1 = con(%layer%dist < 1609, 1, con(%layer%dist < 3218, 0.5,
0))
%layer%s1 = con(slope_p < 10,1, con(slope_p < 30,0.7,con(slope_p < 60,
0.4,0)))
/* compute adjustment from regression equations.
%layer%dis2 = min (%layer%dis1, %layer%s1)
%layer%reg1 = -0.9593 + 0.024 * slope_p - 0.0000523 * %layer%dis1

/* pasture grid
%fence%g = polygrid(%fence%, %fence%#,#,#,10)
&if [exists %pond%t1 -GRID]   &then; kill %pond%t1 all
&if [exists %pond%t2 -GRID]   &then; kill %pond%t2 all
```

```
&if [exists %pond%t3 -GRID]   &then; kill %pond%t3 all
%pond%t1 = isnull(%pond%ws)
%pond%t2 = con( %pond%t1 == 0, %pond%ws, 200)
gridclip %pond%t2 %pond%t3 cover boundary

/* create bu1 and bu2
%layer%bu1 = %fence%g * 100 + range_g
%layer%bu2 = %pond%t3 * 1000000 + %fence%g * 100 + range_g
&if [exists %pond%t1 -GRID]   &then; kill %pond%t1 all
&if [exists %pond%t2 -GRID]   &then; kill %pond%t2 all
&if [exists %pond%t3 -GRID]   &then; kill %pond%t3 all

/* create factor grid
%layer%rock = zonalmean(%layer%bu1, ero_pav, data)
%layer%kls  = zonalmean(%layer%bu1, kls, data)
%layer%sdr  = zonalmean(%layer%bu1, sdr, data)
%layer%adj1 = zonalmean(%layer%bu1, %layer%dis2, data)
%layer%adj2 = zonalmean(%layer%bu1, %layer%reg1, data)

/* create the shape file of basic unit on level 1.
%layer% = gridshape(%layer%bu1, weed)
quit

/* output the label point file
gridpoly %layer%bu1 %layer%bu1p
build
ungenerate point %layer%bu1p %layer%.txt

/* create mask for sample
generate %layer%mask
copytics boundary
input %layer%.txt
point
quit
build %layer%mask point

grid
/* create mask grid
%layer%mg = pointgrid(%layer%mask,#,#,#,10,#)
/* create output for basic unit on level 1
%layer%.out = sample(%layer%mg, %layer%bu1, %layer%adj1, %layer%adj2,
%layer%rock, %layer%kls, %layer%sdr)
quit

tables
/* output the area of each basic unit on level 2
select %layer%bu2.vat
unload %layer%2.out init
quit
quit
```

APPENDIX C PARAMETERS FOR SOUTHEASTERN ARIZONA

Table C-1 Default values of the prices and costs for southeastern Arizona

PRICE ITEM	UNIT	VALUE	SOURCE
price_hay	dollar per pound	0.055	default*
price_bull	dollar per pound	1.54	default*
price_bull_cull	dollar per pound	0.59	default*
price_cow	dollar per pound	0.84	default*
price_cow_cull	dollar per pound	0.48	default*
price_steer_calf	dollar per pound	0.88	default*
price_heifer_calf	dollar per pound	0.8	default*
price_yearling	dollar per pound	0.86	default*
fixed_cost	annual infrastructure fixed cost of a ranch with 40000 acres grazing lands	33400	default*
feed_cost	dollar per head per year	55.78	default*
other_cost	dollar per head per year	60.86	default*
management_cost_ratio	Management cost ratio over gross income	0.06	default*
r	Discount rate	0.08	default*
cost_fence	Cost to add one mile fence in dollar	6395	default*
cost_waterpoint	Cost to add a new water point in dollar	1462	default*
cost_pond	Cost to add a new pond in dollar	1372	default*
cost_dredge_pond	Cost to dredge a pond per ton in dollar	1.25	default*
maintenance_fence	Maintenance cost per year mile in dollar	0	default*
maintenance_waterpoint	Maintenance cost per year per water point in dollar	0	default*
maintenance_pond	Maintenance cost per pond in dollar	0	default*

NOTE: * default source is Teegerstrom and Tronstad (2000)

Table C-2 Vegetation data by ecological site

EID	ECOLOGICAL SITES	PRODUCTION IN EXCELLENT CONDITION (lb/acre)			GRASS PER-CENT (%)	BRUSH GRAZ-ABLE	SOIL DEP-TH*	ECOLOGICAL CONDITION DISCOUNT		
		wet	normal	dry				good	fair	poor
1	Basalt hills 12-16 PZ	1300	900	600	0.65	0.225	0	0.82	0.59	0.45
2	Clayey bottom 12-16 PZ	2500	2000	800	0.9	0.085	1	0.88	0.76	0.48
3	Clayey upland 12-16 PZ	1500	1000	600	0.85	0.07	1	0.68	0.52	0.36
4	Granitic hills 12-16 PZ	1600	900	600	0.6	0.275	0	0.80	0.56	0.40
5	Limestone hills 12-16 PZ	1000	700	500	0.625	0.2	0	0.85	0.65	0.50
6	Limy slopes 12-16 PZ	1500	900	600	0.7	0.25	0	0.85	0.65	0.50
7	Limy upland 12-16 PZ	900	600	350	0.325	0.275	0	0.65	0.47	0.35
8	Loamy bottom 12-16 PZ	3000	1800	800	0.7	0.175	1	0.80	0.60	0.40
9	Loamy upland12-16 PZ	1800	1100	600	0.8	0.135	1	0.75	0.63	0.42
10	Sandy bottom 12-16 PZ	3000	2000	1000	0.475	0.275	1	0.62	0.45	0.31
11	Sandy loam (deep) 12-16 PZ	1500	1000	650	0.75	0.225	1	0.72	0.50	0.33
12	Sandy loam upland 12-16 PZ	2000	1200	700	0.825	0.175	1	0.74	0.46	0.31
13	Shallow upland 12-16 PZ	900	650	400	0.75	0.175	0	0.76	0.65	0.53
14	Shallow hills (QUEM) 16-20 PZ	1200	900	600	0.6	0.3	0	0.88	0.61	0.52
15	Loamy upland 16-20 PZ	1600	1350	1000	0.85	0.15	1	0.54	0.42	0.38
16	Shallow hills 16-20 PZ	1200	900	600	0.6	0.3	0	0.88	0.70	0.59

NOTE: * SOIL DEPTH is estimated from ecological site report, 1 deep; 0 shallow.
Arizona Ecological Site Guide (NRCS), all sites are from MLRA 41, southeastern AZ.

Table C-3 Look-up table for conversion of soil types to K values

SOIL TYPE	K Factor	SOIL TYPE	K Factor
Baboquivari	0.20	Luckyhills	0.17
Combate	0.17	McNeal	0.05
Blacktail	0.15	Mabray	0.05
Budlamp	0.10	Chiricahua	0.10
Woodcutter	0.10	McAllister	0.17
Chiricahua	0.10	Monterosa	0.10
Elgin	0.10	Riverwash	0.02
Stronghold	0.10	Bodecker	0.17
Epitaph	0.10	Schiefflin	0.10
Forrest	0.20	Bernardino	0.05
Bonita	0.32	Sutherland	0.05
Graham	0.17	Mule	0.05
Lampshire	0.05	Tombstone	0.05
Grizzle	0.17	Woodcutter	0.10
Rock outcrop	0.00		

Table C-4 AUM requirements of livestock

TYPE	AUM Equivalent
Cow/calf	1.0
Bull	1.35
Yearling	0.7
Horse	1.25

APPENDIX D DATA FOR THE WALNUT GULCH WATERSHED

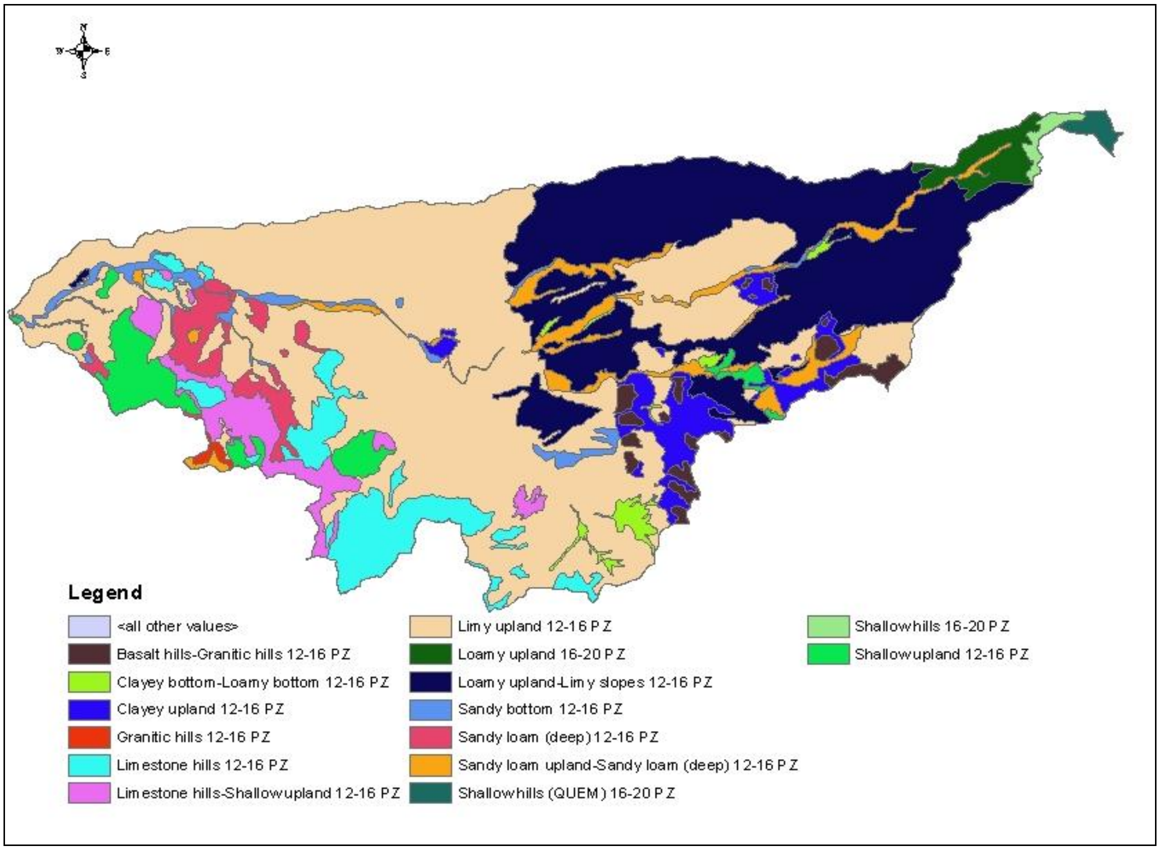


Figure D-1 The ecological site map of the Walnut Gulch Watershed

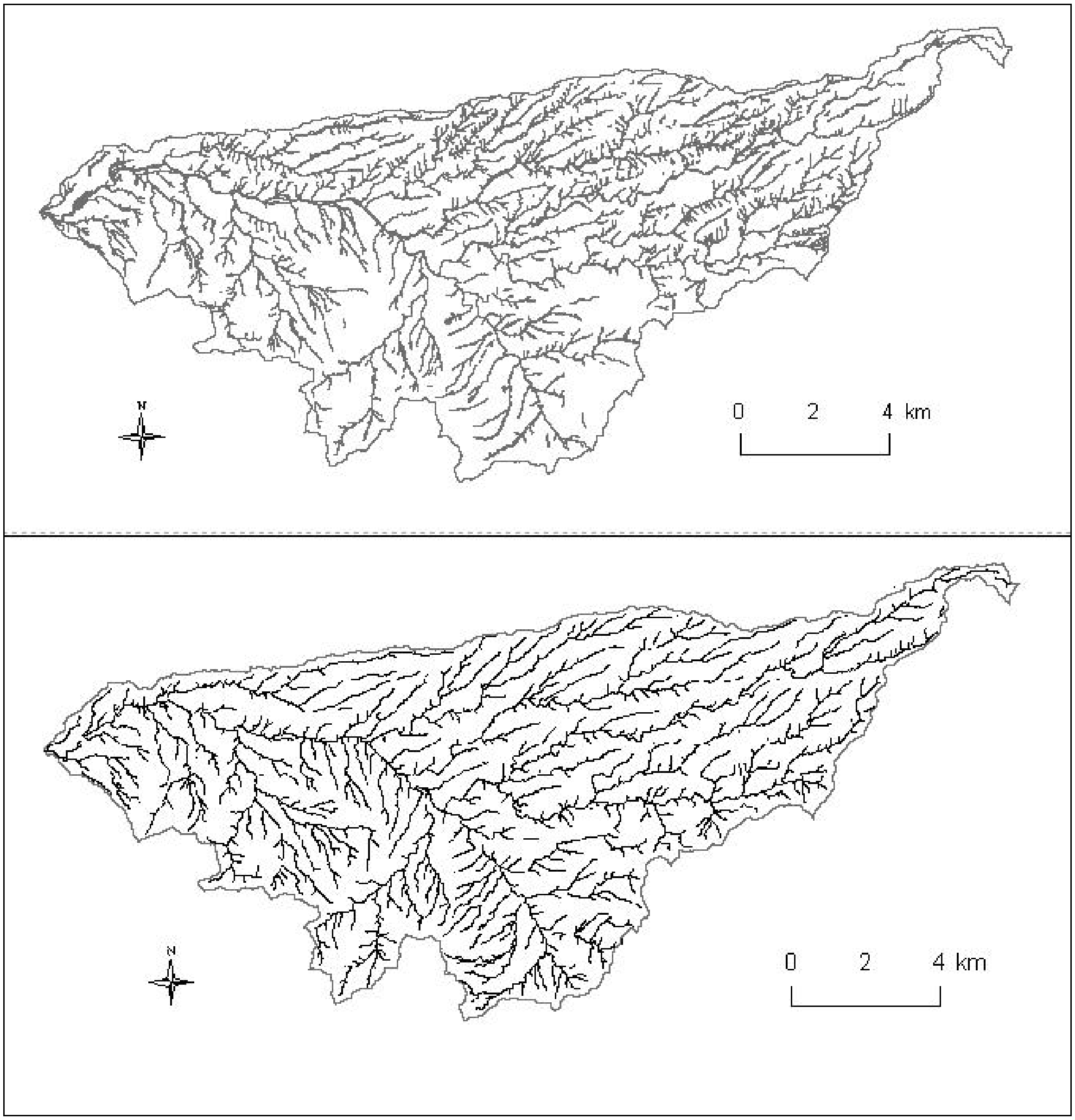


Figure D-2 Channel networks from survey (top) and from 10 meter DEM processing (bottom) of the Walnut Gulch Watershed

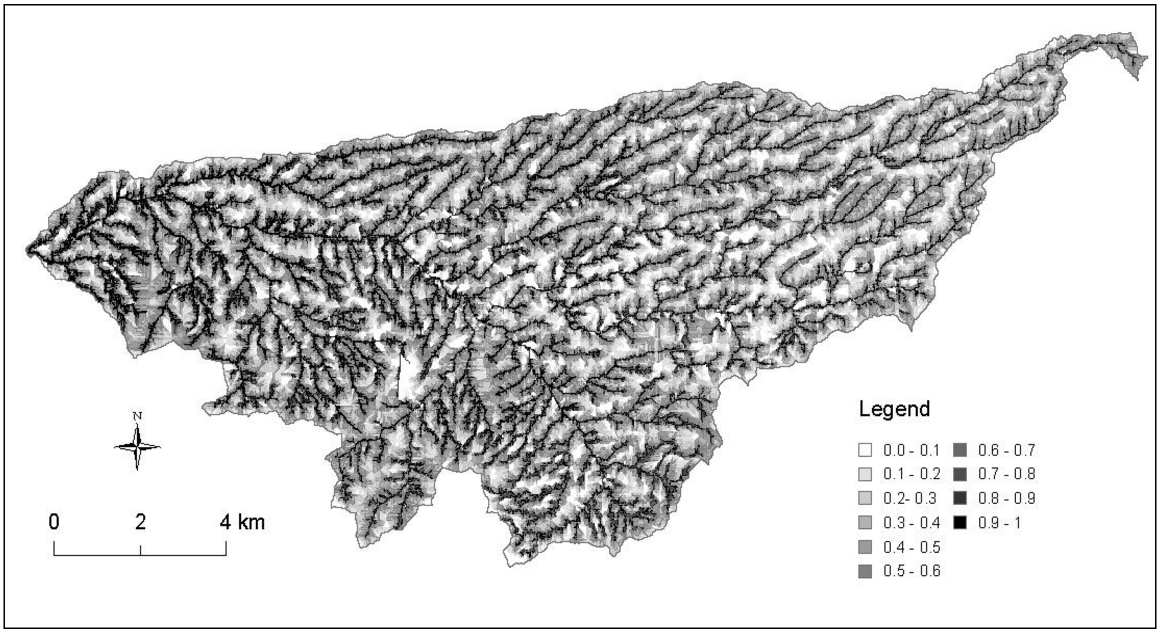


Figure D-3 Estimated sediment delivery ratio for the Walnut Gulch Watershed

APPENDIX E SAMPLE OUTPUTS OF CASE STUDY

Table E-1 Sample economic budget of the default project budget

BREED HERD SIZE:	276	CALF CROP PERCENTAGE:	80.0%
CULL RATE:	20.0%	CALF HEIFERS KEPT:	70.0%

REVENUES					
ITEM	**QUANTITY (heads)**	**WEIGHT (lbs/head)**	**PRICE**	**UNIT**	**VALUE $**
Steer Calves	107	450.0	0.88	dollar per pound	$42,372.00
Heifer Calves	32	425.0	0.8	dollar per pound	$10,880.00
Cull Cows	55	900.0	0.48	dollar per pound	$23,760.00
Cull Bulls	3	1300.0	0.59	dollar per pound	$2,301.00
				TOTAL REVENUES	**$79,313.00**

VARIABLE COSTS			
ITEM	**COST ($/head)**	**# heads**	**VALUE $**
FEED COSTS	55.78	276	$15,395.28
OTHER VARIABLE COSTS	60.86	276	$16,797.36
INTEREST COSTS (at APR 8.0%)			$2,672.70
		TOTAL VARIABLE COST	**$34,768.05**
		GROSS RETURNS	**$44,544.95**
OTHER COSTS			
MANAGEMENT & OPERATION COSTS (6% of gross income)			$2,672.70
BMP COSTS			$301.00
FIXED COSTS			$41,003.25
		TOTAL COSTS	**$78,745.00**
		PROFIT	**$568.00**

Table E-2 Sample forage budget of the default project

PASTURE #	AREA (acres)	TOTAL GRASS PRODUCTION (AUYs/year)	TOTAL BRUSH & FORB PRODUCTION (AUYs/year)	TOTAL GRASS GRAZED (AUYs/year)	TOTAL BRUSH & FORB GRAZED (AUYs/year)	AVERAGE CANOPY COVER (%)	AVERAGE GROUND COVER (%)
2	756.0	33.8	12.2	12.2	0.6	6.6	19.8
3	1334.8	65.6	19.7	24.5	0.8	6.2	20.6
4	1871.4	90.1	31.4	38.8	1.6	7.0	19.5
5	247.3	12.3	4.1	4.8	0.2	7.0	21.0
6	478.0	21.5	8.2	10.5	0.5	7.0	16.8
7	2389.1	23.9	48.1	10.0	3.3	7.1	8.2
8	138.2	1.3	2.7	0.6	0.2	7.0	8.0
9	612.1	30.4	10.2	11.7	0.5	7.0	21.0
10	19.8	0.3	0.4	0.0	0.0	8.0	13.9
11	2213.7	35.7	45.9	15.9	3.3	7.3	10.2
12	676.0	33.6	11.2	13.7	0.5	7.0	20.0
13	352.9	7.2	6.9	3.1	0.5	7.1	11.3
14	8574.0	259.1	159.0	103.6	9.2	7.1	14.4
15	831.0	12.2	16.2	5.7	1.2	7.0	9.4
16	17.6	0.2	0.3	0.0	0.0	8.0	11.0
17	738.9	32.9	12.6	13.2	0.6	6.9	18.7
18	4156.6	109.5	73.6	40.1	4.1	6.7	13.6
19	1305.1	45.1	21.4	17.4	1.0	6.5	16.0
20	1265.0	14.2	25.2	5.8	1.6	7.1	8.6
21	1553.1	66.3	19.8	25.9	0.8	5.5	17.4
22	3020.9	70.0	53.8	24.0	2.6	6.8	12.7
23	98.4	3.2	1.4	1.3	0.1	5.7	14.7
24	854.4	16.1	17.1	7.6	1.2	7.3	10.6
25	2.6	0.0	0.1	0.0	0.0	8.0	11.0

Table E-3 Sample sediment budget of pastures of the default project

PASTURE #	AREA (acres)	TOTAL EROSION (tons/year)	SEDIMENT YIELD (tons/year)	SEDIMENT DETAINED IN PONDS (tons/year)
2	756.0	542.2	171.9	0.4
3	1334.8	705.8	186.8	37.6
4	1871.4	542.7	103.3	97.8
5	247.3	81.6	9.0	22.4
6	478.0	74.6	15.8	16.7
7	2389.1	1491.6	534.0	29.6
8	138.2	76.0	28.2	0.0
9	612.1	257.3	75.9	0.0
10	19.8	8.8	3.7	0.0
11	2213.7	1281.1	451.0	22.9
12	676.0	280.2	65.4	22.7
13	352.9	87.6	29.3	0.0
14	8574.0	3449.2	1097.2	142.9
15	831.0	498.0	183.9	0.0
16	17.6	8.3	2.9	1.0
17	738.9	320.8	104.9	0.0
18	4156.6	1898.6	754.8	0.0
19	1305.1	731.9	197.4	21.4
20	1265.0	933.7	289.4	17.3
21	1553.1	1151.8	284.7	112.9
22	3020.9	1025.2	381.7	16.8
23	98.4	41.2	15.3	0.0
24	854.4	369.5	34.5	121.7
25	2.6	1.2	0.3	0.0

Table E-4 Sediment budget of ponds of the default project

POND #	AREA (acres)	SEDIMENT DETAINED (tons/year)
201	77.2	22.9
207	209.2	48.1
208	257.9	15.6
209	367.4	33.1
210	173.4	18.5
212	764.7	133.2
213	360.4	117.2
214	357.9	46.3
215	91.7	21.2
216	220.0	26.8
217	176.7	51.8
218	148.3	22.3
219	102.3	21.4
220	130.9	22.7
221	148.5	32.7
223	115.1	30.6
226	84.6	19.9

APPENDIX F AGWA/SWAT SIMULATION

The Walnut Gulch Experimental Watershed has long-term records of runoff at major flumes, but does not have long-term observed data on sediment yield. To further test the SDSS prediction in Chapter 5, SWAT (Soil & Water Assessment Tool), a distributed watershed model, was used to estimate sediment yield based on historic precipitation data. SWAT simulates the hydrologic and erosion response on the watershed level. AGWA (Automated Geospatial Watershed Assessment) provides a simple GIS interface to parameterize and run the SWAT. This study used the AGWA 1.4 package downloaded from (http://www.tucson.ars.ag.gov/agwa/**).**

The major inputs were created from the embedded data in AGWA. A 10-meter USGS DEM of Walnut Gulch was used to delineate the watershed and to create hydraulic geometry relationships with the contributing area threshold of 3% of total watershed. The vegetation parameters were derived from the North American Land Cover (NALC) Characterization 1992 map of the San Pedro Basin. The soil parameters were derived from the Soil Survey Geographic (SSURGO) map of the San Pedro Basin. The historic daily precipitation data of Walnut Gulch Watershed were downloaded from the website **(**http://www.tucson.ars.ag.gov/dap/). The precipitation data were from 1960 to 1996 for all 93 rain gauge stations that have regular precipitation records. The records during station closures that occurred mainly in the dry season weree treated as zero.

After all inputs were defined, SWAT simulated the runoff and sediment yields for the 37-year period. The results simulated the average annual runoff at Flume 1, of 4.7mm, higher than the observed runoff, 2.8 mm. However, the simulated sediment yield for Flume 1 was about 145 tons/year and many hydrological units have a zero sediment yield, which is significantly lower than the reported results.

After consulting Dr. Mariano Hernandez in the SWRC ARS USDA, some parameters were changed from the default values. The default C value for range brush was changed from 0.003 to 0.1. The channel slopes from AGWA 1.4 were incorrectly estimated and written to the input files for SWAT. To correct the errors, the slopes of each channel were also manually calculated through the DEM and channel network layers. The sediment transport coefficients in the Bagnold's equation were also modified. In the *.bsn file, line 14 was set as PRF = 1.0, line 15 was set SPCON = 0.01, line 16 was set as SPEXP = 2.0. In each *.rte file, line 4 was set as the correct slope, line 7 was set as CH_K(2) = 50.00, line 8 was set as CH_EROD = 0.50.

After this change, the annual simulated sediment yield at Flume 1 was much closer to the reported value. The annual simulated runoff at Flume 1 generally overestimated the runoff (Table F-1). Figure F-1 shows the comparison of the simulated and observed runoff. The monthly simulated runoff could underestimate or overestimate the runoff. The errors in runoff estimation could cause the bias in sediment yield estimation. The SWAT estimated sediment yield at Flume 1 was higher than the total upland erosion of the Walnut Gulch Watershed, which means a significant percent of sediment yield is from channel erosion. The upland erosion from SDSS and SWAT is very close, but the SDSS predicted much lower sediment yield because the SDSS model ignored the channel erosion and used sediment delivery ratios less than 1, which assumes sediment deposition during sediment transportation.

Table F-1 Comparison of SWAT simulation and observed data at Flume 1 of Walnut Gulch Watershed

	Summer [1,2]	Annual [2]
Observed Runoff (mm)	2.7	2.8
SWAT Simulated Runoff (mm)	4.3	6.9
SWAT Simulated Sediment Yield (tons/year)	17729	31900
SWAT Simulated Upland Erosion (tons/year)	12900	14800
SDSS Predicted Sediment Yield (tons/year)	5030	5030
SWAT Predicted Upland Erosion (tons/year)	15890	15890

Note: [1] summer months include July, August, and September.
[2] study period from 01/1960 — 12/1996.

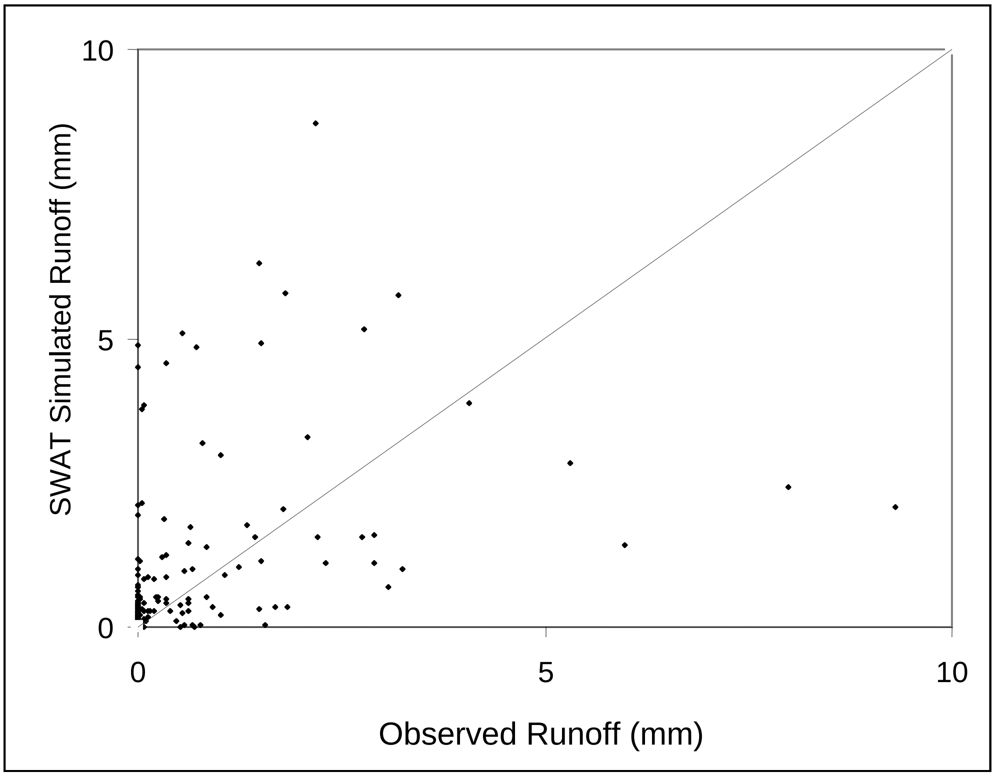


Figure F-1 Comparison of the observed runoff vs. SWAT simulated runoff at Flume 1 in different months

APPENDIX G SCREEN CAPTURES OF SDSS INTERFACES

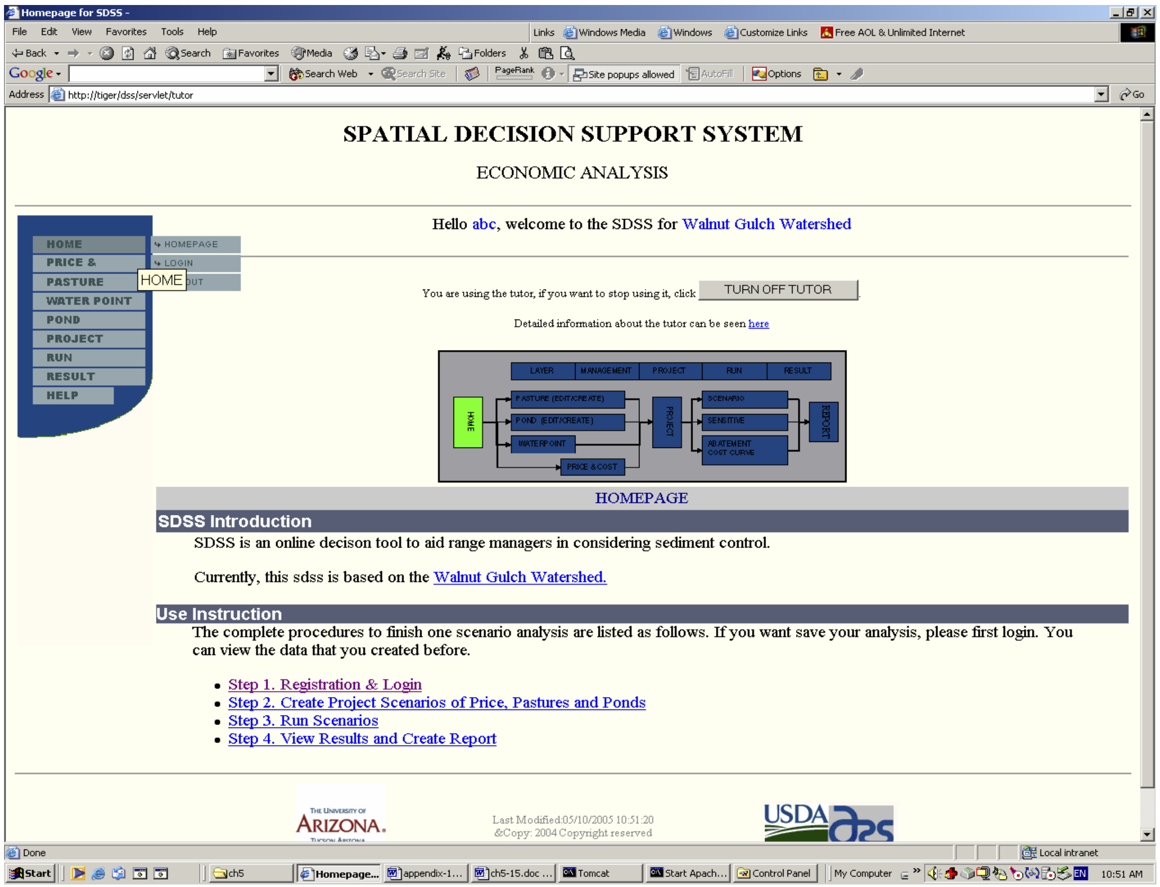
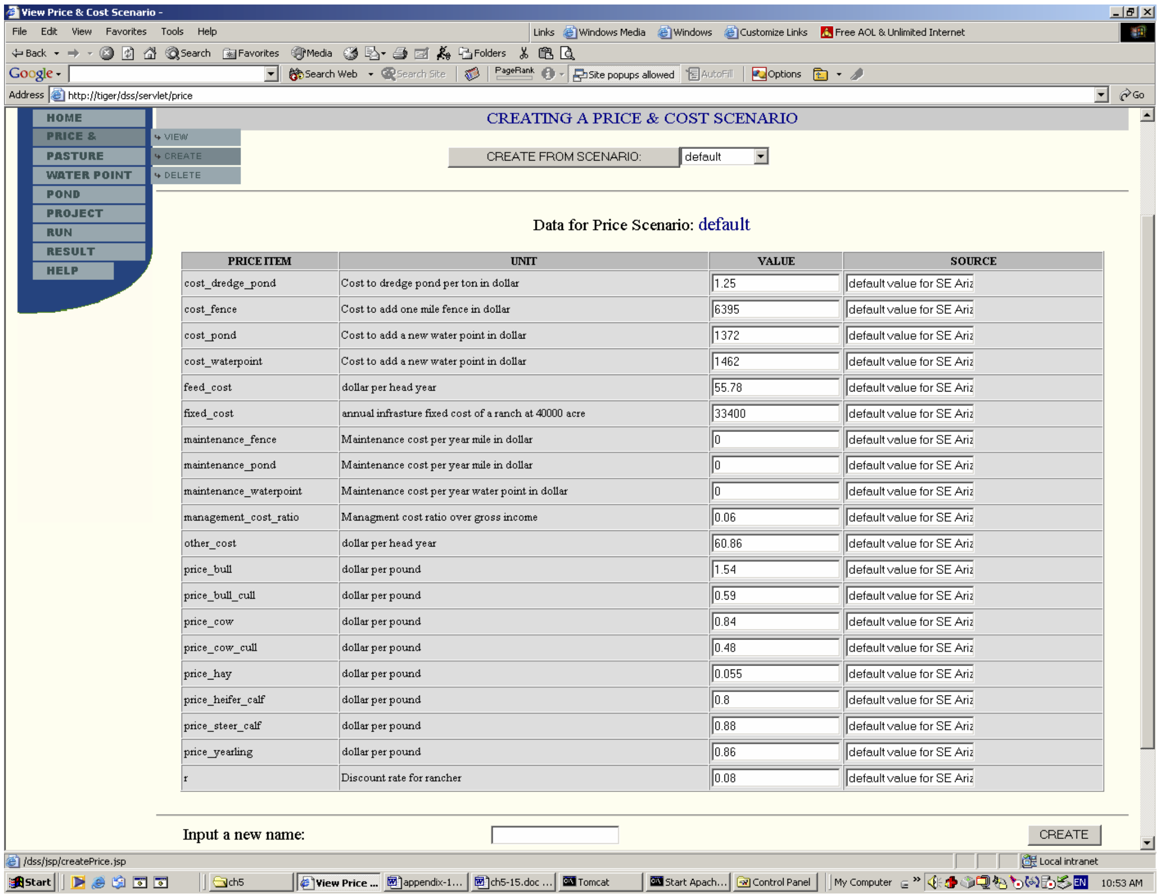


Figure G-1 Screen capture of Homepage



PRICE ITEM	UNIT	VALUE	SOURCE
cost_dredge_pond	Cost to dredge pond per ton in dollar	1.25	default value for SE Ariz
cost_fence	Cost to add one mile fence in dollar	6395	default value for SE Ariz
cost_pond	Cost to add a new water point in dollar	1372	default value for SE Ariz
cost_waterpoint	Cost to add a new water point in dollar	1462	default value for SE Ariz
feed_cost	dollar per head year	55.78	default value for SE Ariz
fixed_cost	annual infrasture fixed cost of a ranch at 40000 acre	33400	default value for SE Ariz
maintenance_fence	Maintenance cost per year mile in dollar	0	default value for SE Ariz
maintenance_pond	Maintenance cost per year mile in dollar	0	default value for SE Ariz
maintenance_waterpoint	Maintenance cost per year water point in dollar	0	default value for SE Ariz
management_cost_ratio	Managment cost ratio over gross income	0.06	default value for SE Ariz
other_cost	dollar per head year	60.86	default value for SE Ariz
price_bull	dollar per pound	1.54	default value for SE Ariz
price_bull_cull	dollar per pound	0.59	default value for SE Ariz
price_cow	dollar per pound	0.84	default value for SE Ariz
price_cow_cull	dollar per pound	0.48	default value for SE Ariz
price_hay	dollar per pound	0.055	default value for SE Ariz
price_heifer_calf	dollar per pound	0.8	default value for SE Ariz
price_steer_calf	dollar per pound	0.88	default value for SE Ariz
price_yearling	dollar per pound	0.86	default value for SE Ariz
r	Discount rate for rancher	0.08	default value for SE Ariz

Figure G-2 Screen capture of creating a new price & cost scenario

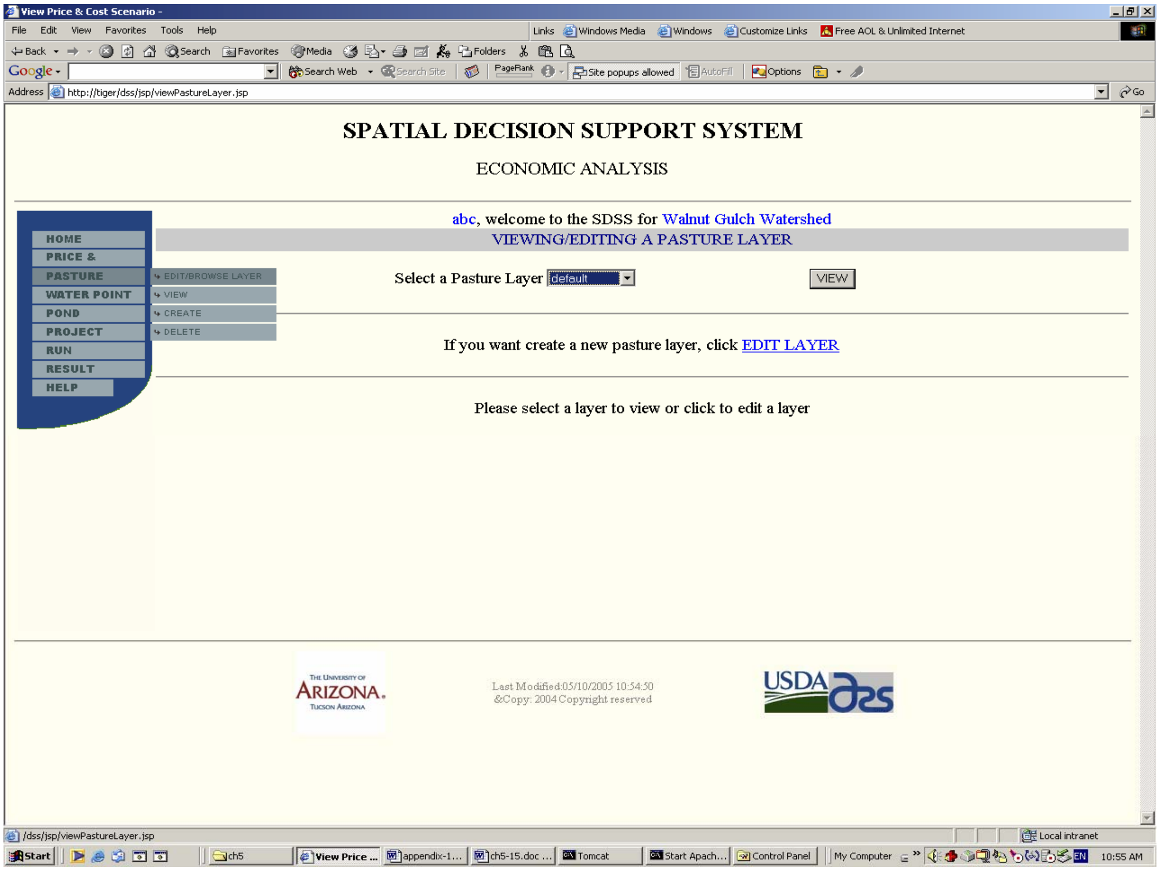


Figure G-3 Screen capture of the JSP page to view or edit pasture layers

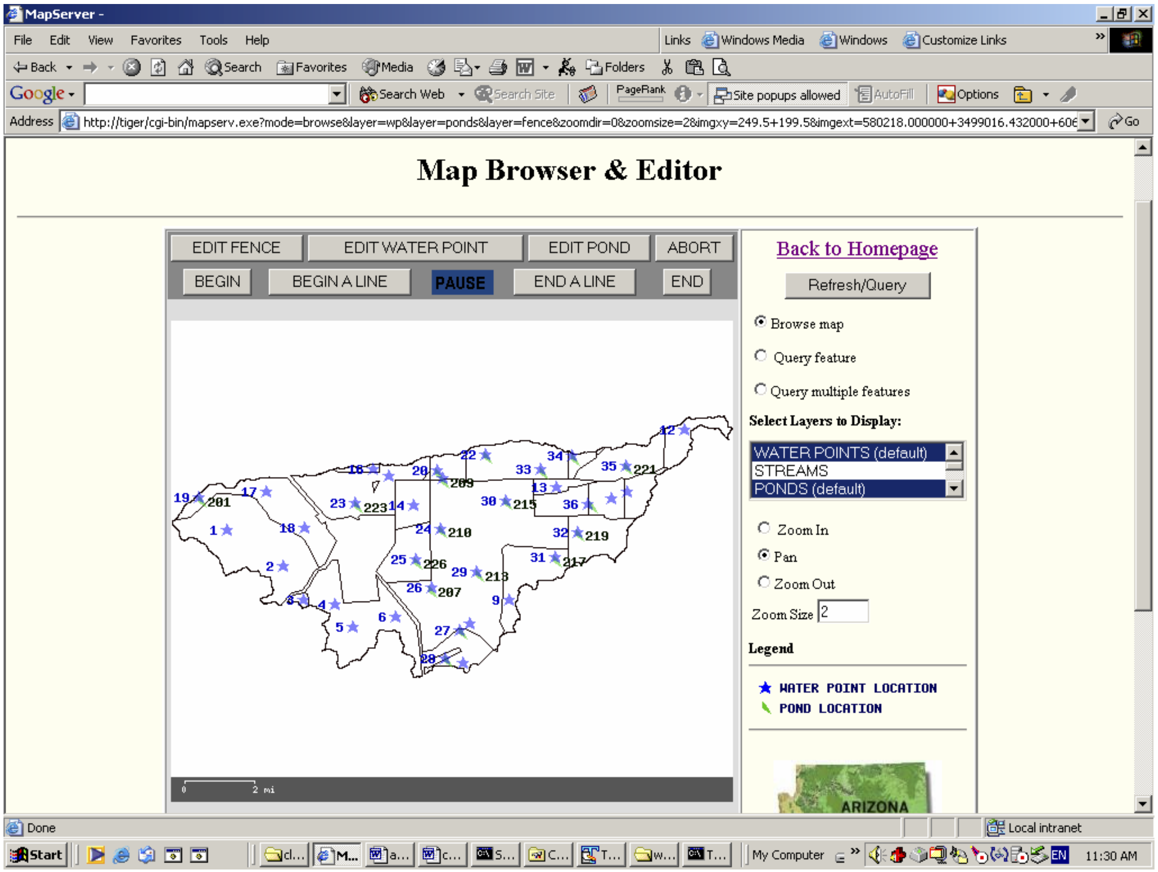


Figure G-4 Screen capture of the map editor

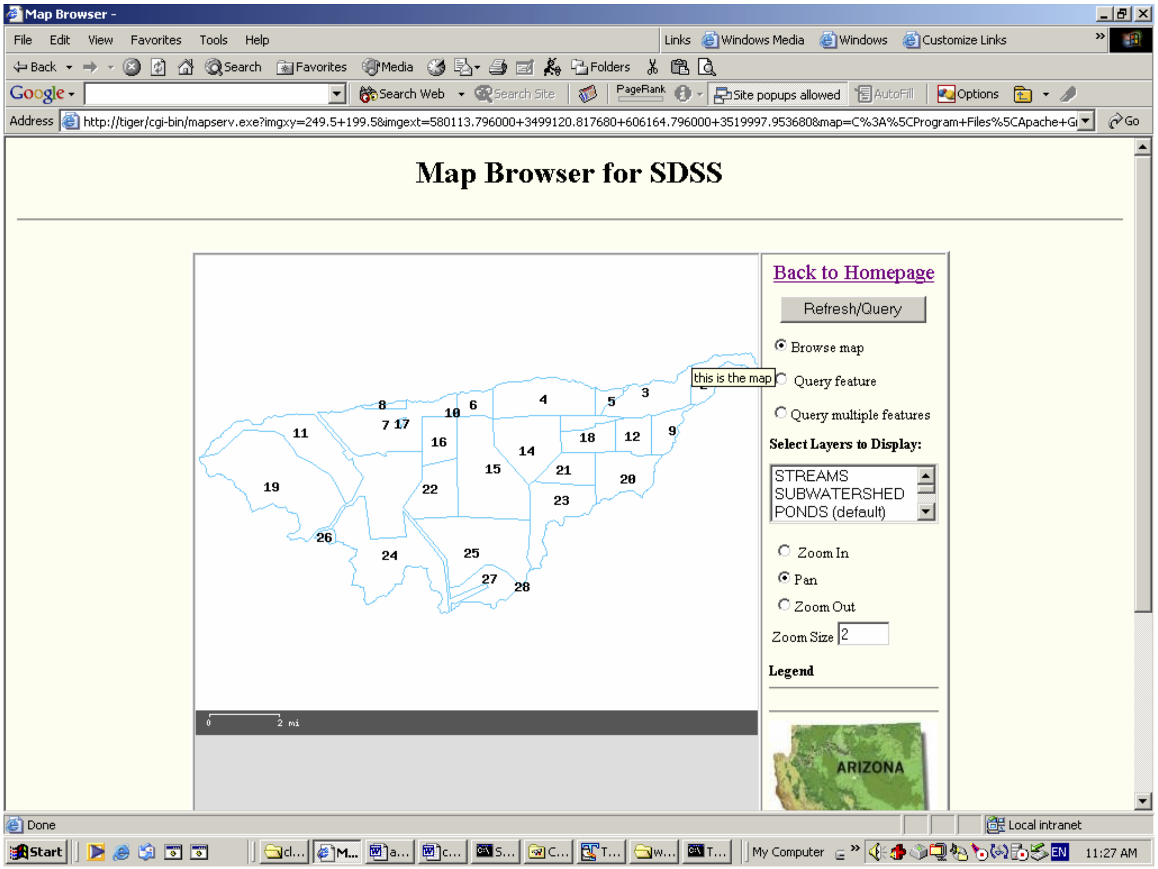


Figure G-5 Screen capture of the map browser

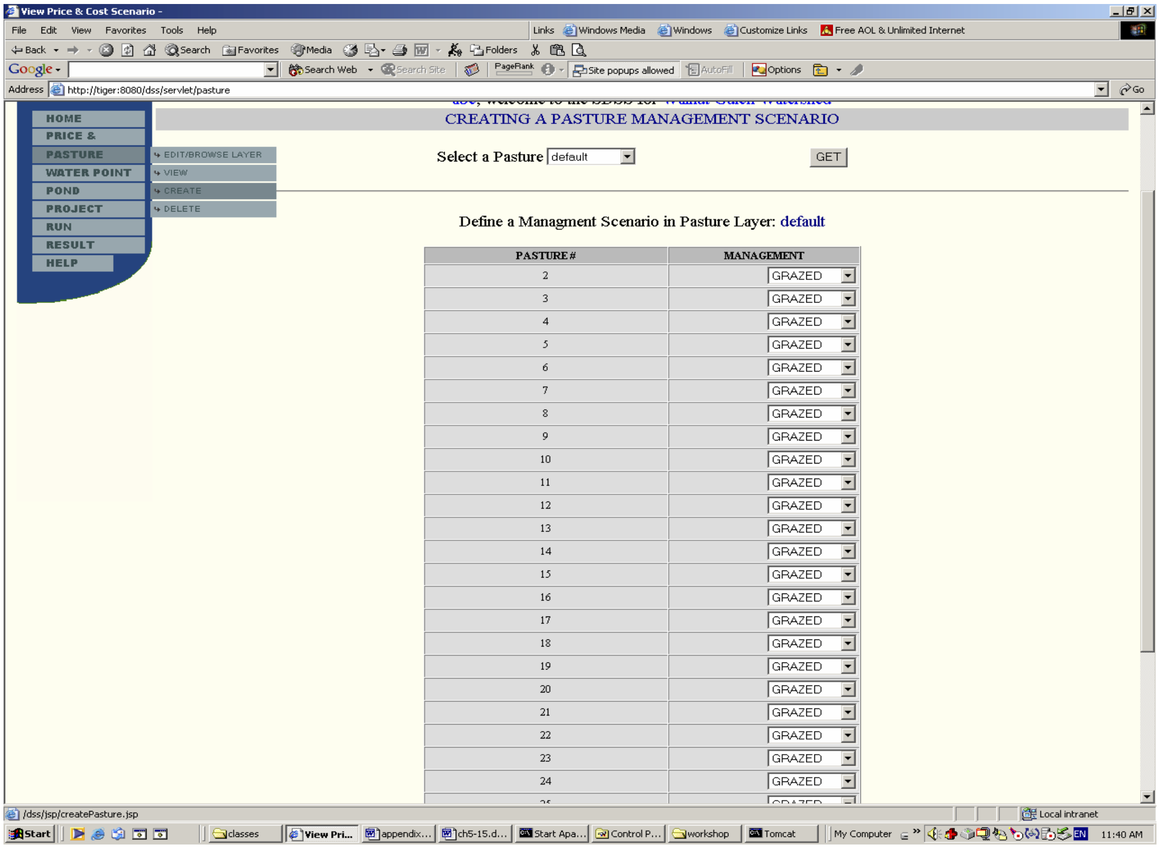


Figure G-6 Screen capture of creating a pasture management scenario

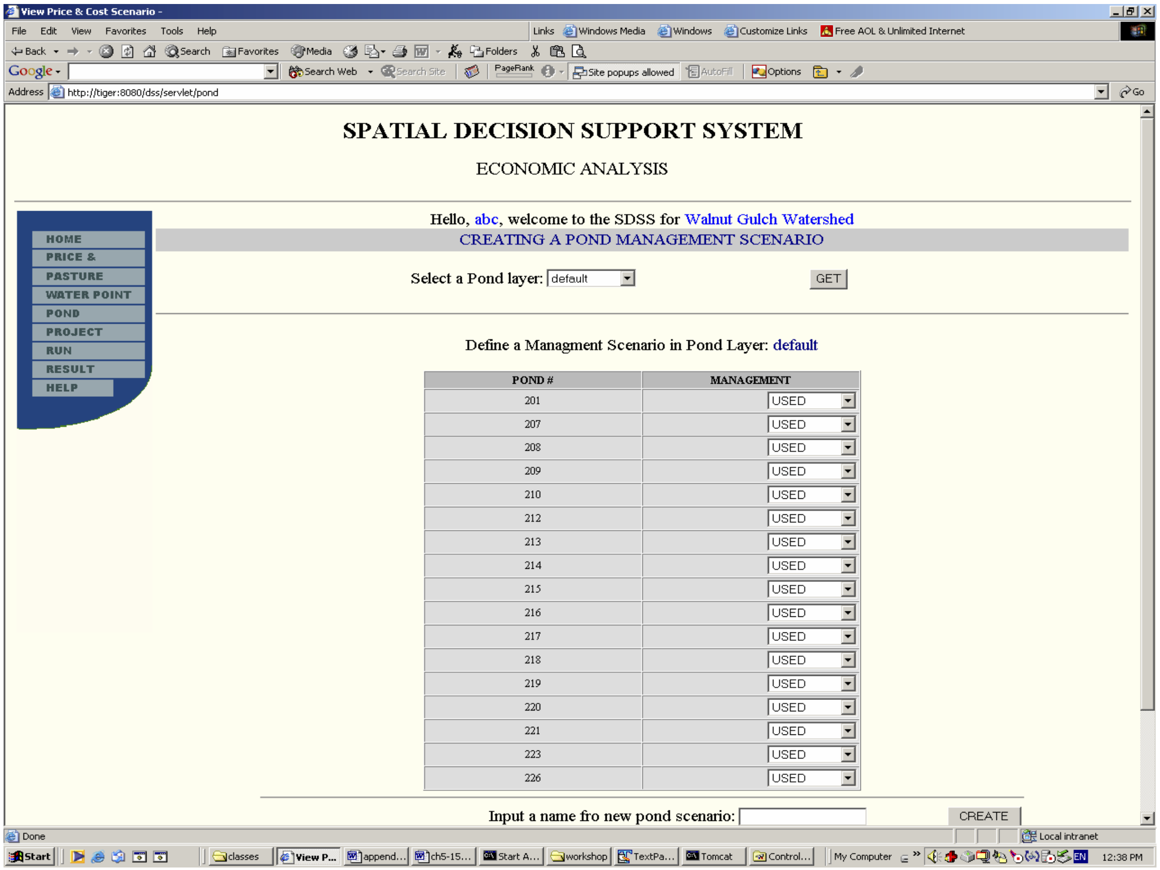


Figure G-7 Screen capture of defining a pond management scenario

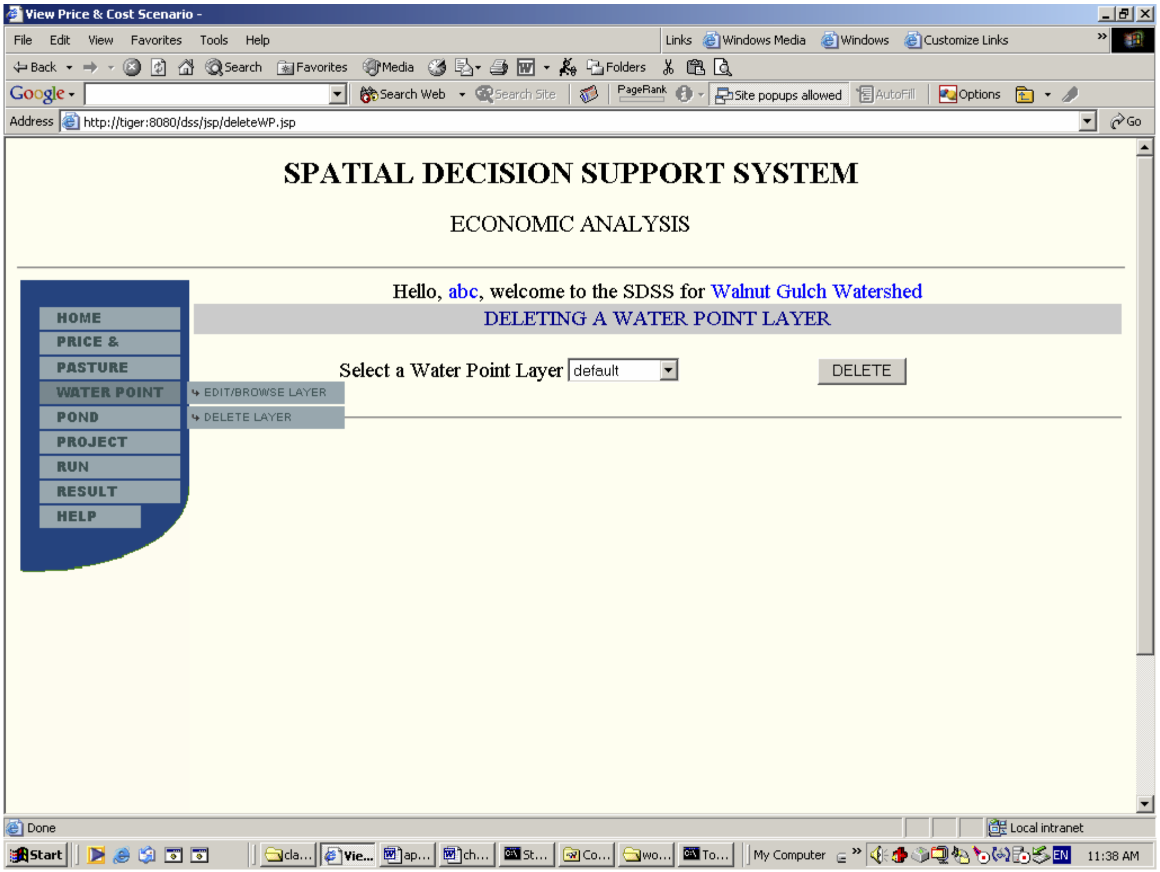


Figure G-8 Screen capture of deleting a water point layer

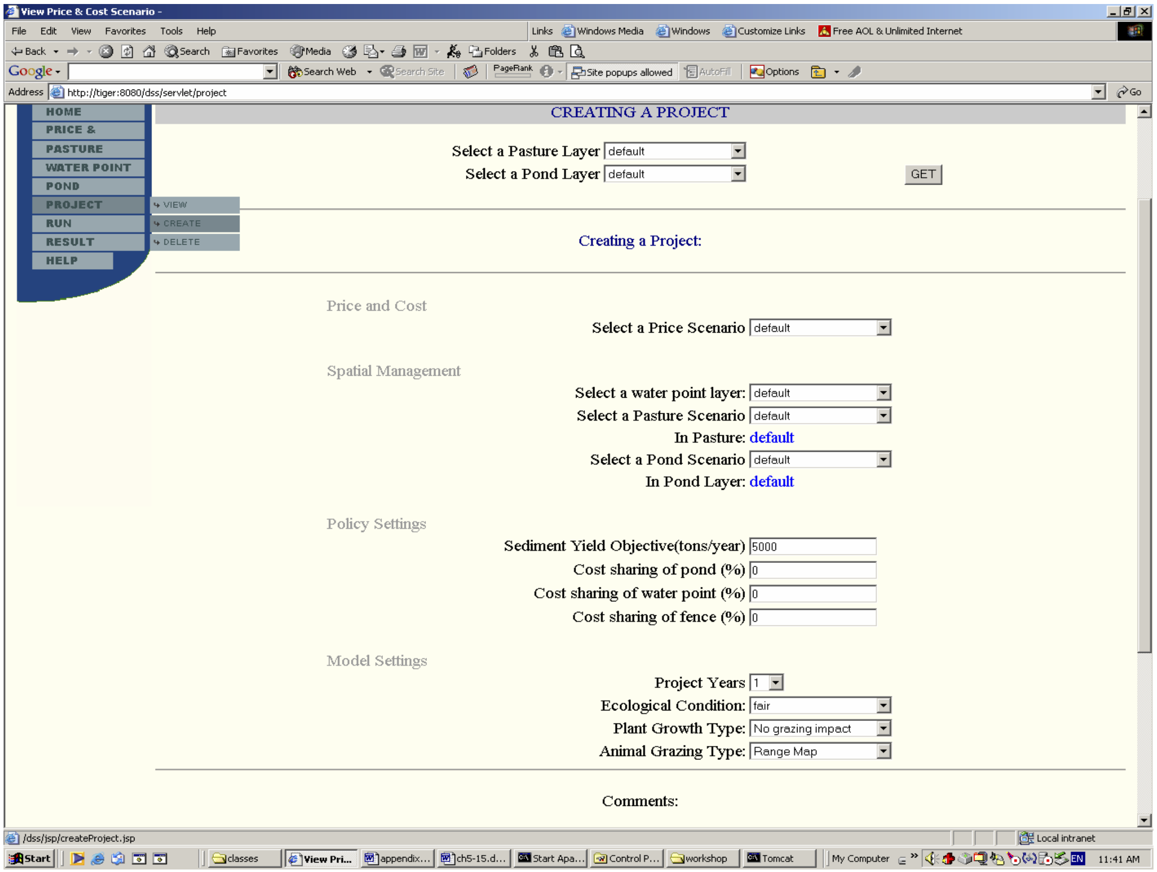


Figure G-9 Screen capture of creating a project

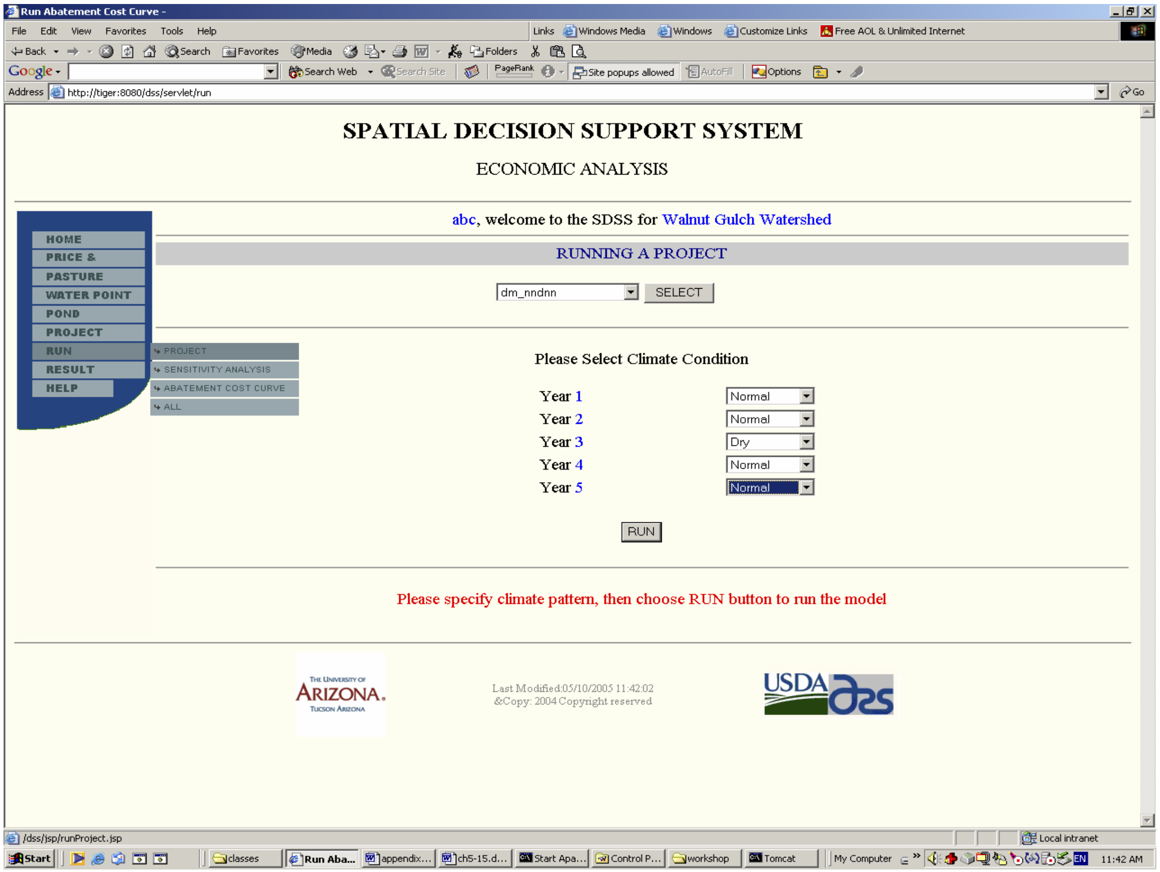


Figure G-10 Screen capture of running a project

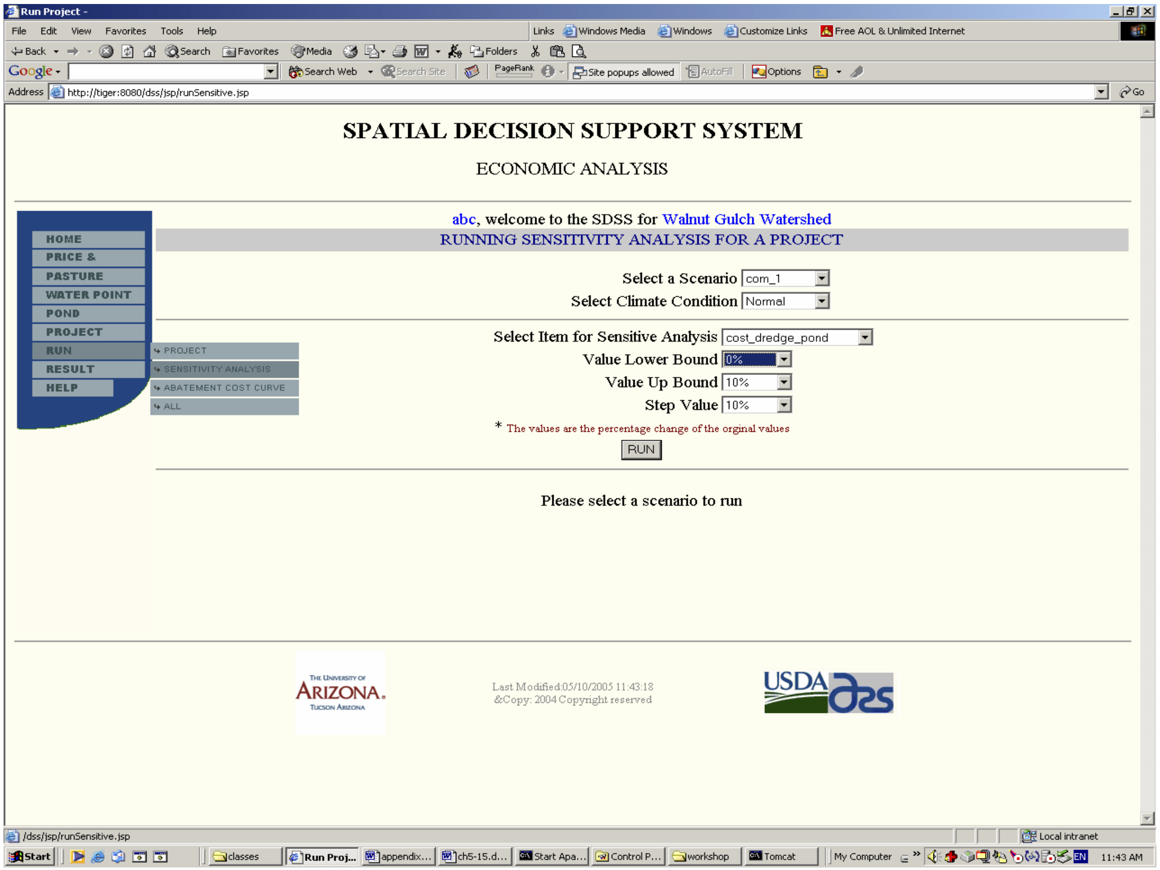


Figure G-11 Screen capture of running a sensitivity analysis

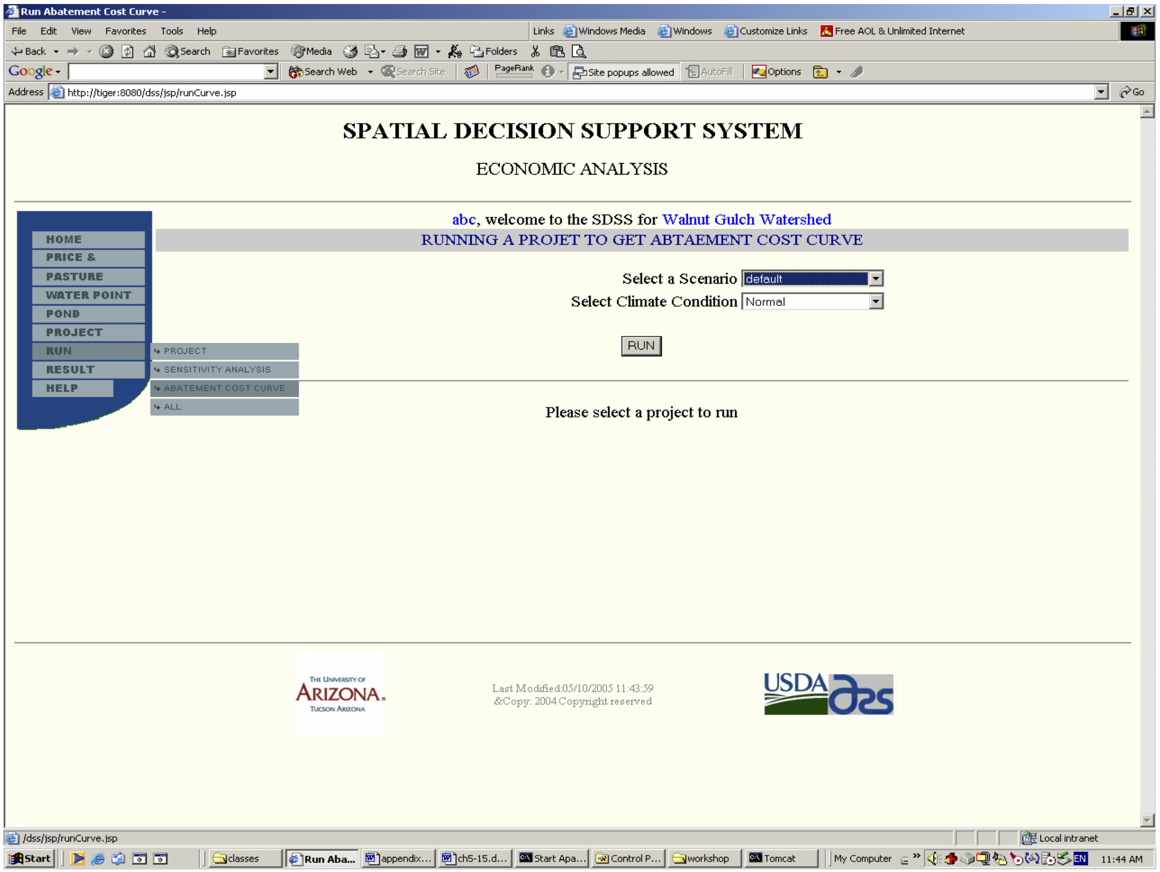


Figure G-12 Screen capture of running a project to get abatement cost curve

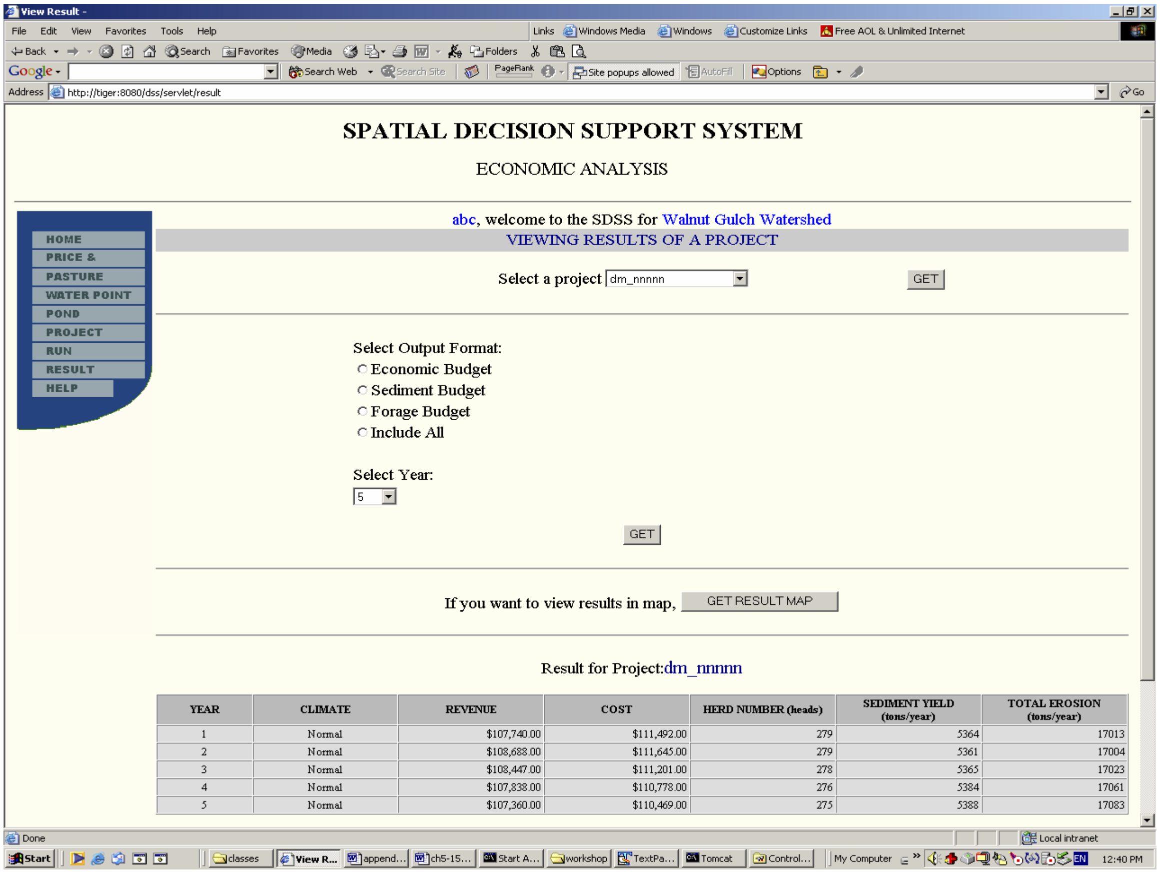
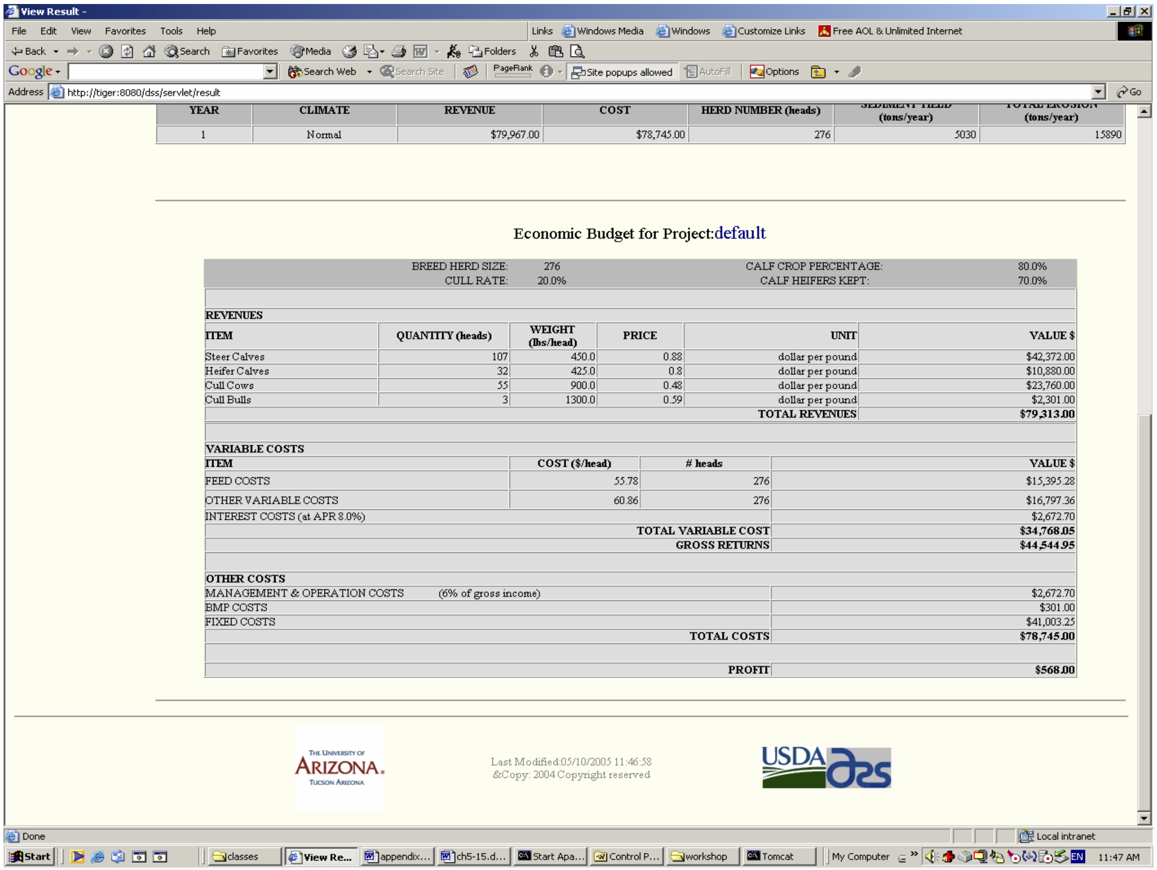


Figure G-13 Screen capture of viewing the result summary



YEAR	CLIMATE	REVENUE	COST	HERD NUMBER (heads)	SEDIMENT YIELD (tons/year)	TOTAL EROSION (tons/year)
1	Normal	$79,967.00	$78,745.00	276	5030	15890

Economic Budget for Project:default

BREED HERD SIZE:	276	CALF CROP PERCENTAGE:	80.0%
CULL RATE:	20.0%	CALF HEIFERS KEPT:	70.0%

REVENUES

ITEM	QUANTITY (heads)	WEIGHT (lbs/head)	PRICE	UNIT	VALUE $
Steer Calves	107	450.0	0.88	dollar per pound	$42,372.00
Heifer Calves	32	425.0	0.8	dollar per pound	$10,880.00
Cull Cows	55	900.0	0.48	dollar per pound	$23,760.00
Cull Bulls	3	1300.0	0.59	dollar per pound	$2,301.00
				TOTAL REVENUES	**$79,313.00**

VARIABLE COSTS

ITEM	COST ($/head)	# heads	VALUE $
FEED COSTS	55.78	276	$15,395.28
OTHER VARIABLE COSTS	60.86	276	$16,797.36
INTEREST COSTS (at APR 8.0%)			$2,672.70
		TOTAL VARIABLE COST	**$34,768.05**
		GROSS RETURNS	**$44,544.95**

OTHER COSTS

MANAGEMENT & OPERATION COSTS	(6% of gross income)	$2,672.70
BMP COSTS		$301.00
FIXED COSTS		$41,003.25
	TOTAL COSTS	**$78,745.00**
	PROFIT	**$568.00**

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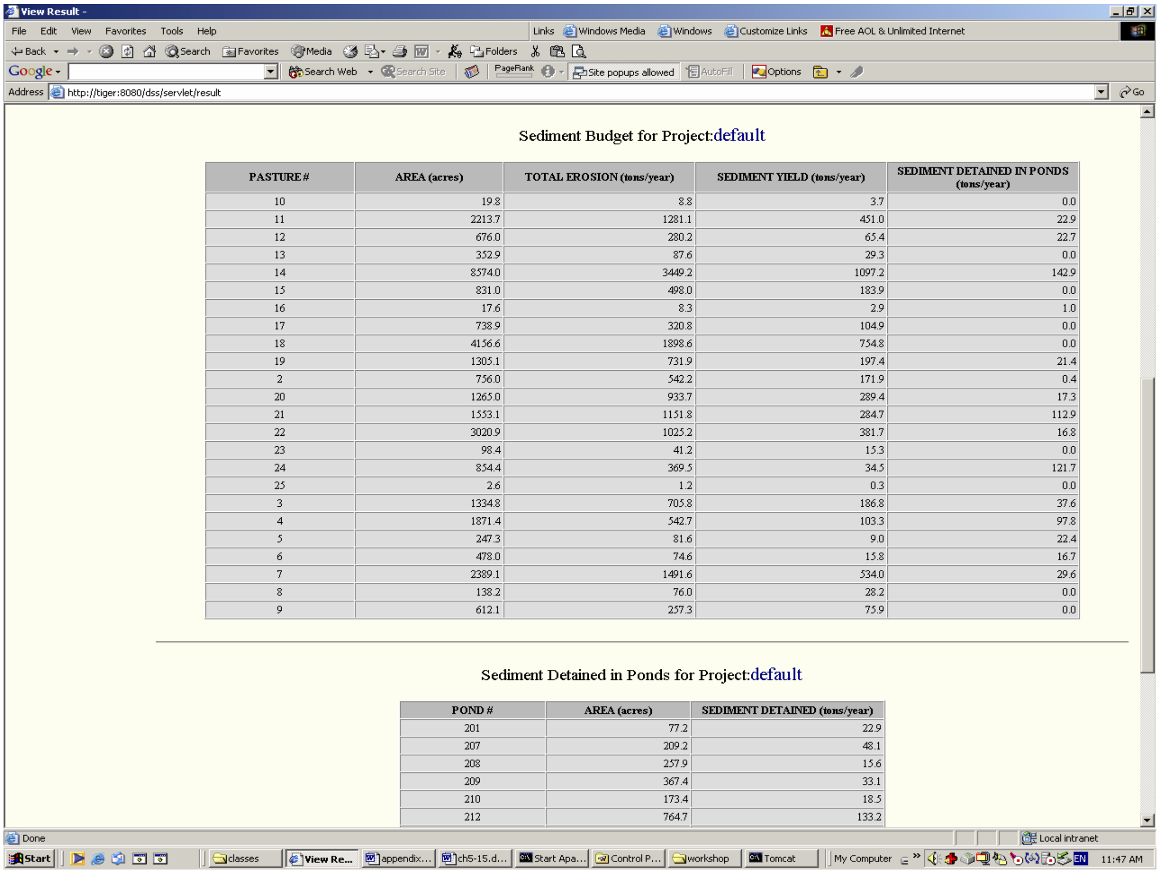
Figure G-14 Screen capture of viewing the economic budget



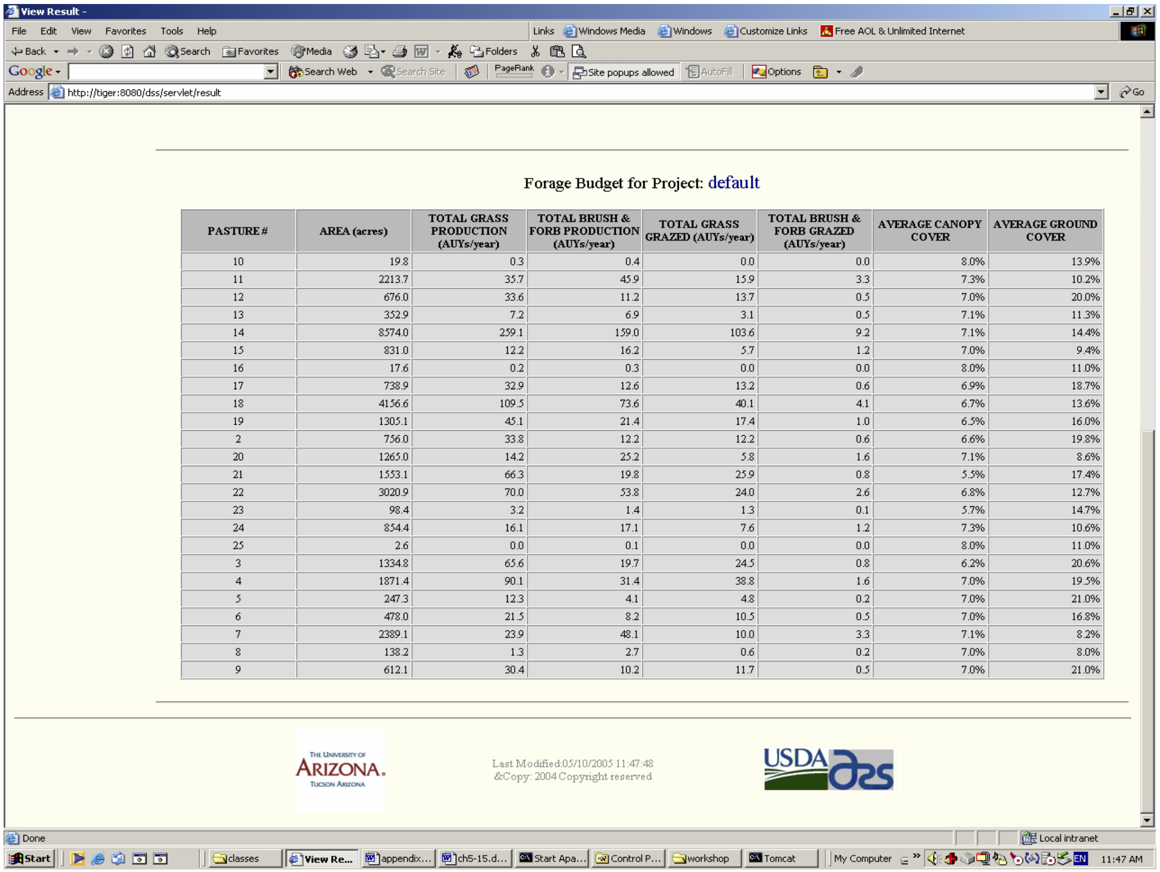
Sediment Budget for Project:default

PASTURE #	AREA (acres)	TOTAL EROSION (tons/year)	SEDIMENT YIELD (tons/year)	SEDIMENT DETAINED IN PONDS (tons/year)
10	19.8	8.8	3.7	0.0
11	2213.7	1281.1	451.0	22.9
12	676.0	280.2	65.4	22.7
13	352.9	87.6	29.3	0.0
14	8574.0	3449.2	1097.2	142.9
15	831.0	498.0	183.9	0.0
16	17.6	8.3	2.9	1.0
17	738.9	320.8	104.9	0.0
18	4156.6	1898.6	754.8	0.0
19	1305.1	731.9	197.4	21.4
2	756.0	542.2	171.9	0.4
20	1265.0	933.7	289.4	17.3
21	1553.1	1151.8	284.7	112.9
22	3020.9	1025.2	381.7	16.8
23	98.4	41.2	15.3	0.0
24	854.4	369.5	34.5	121.7
25	2.6	1.2	0.3	0.0
3	1334.8	705.8	186.8	37.6
4	1871.4	542.7	103.3	97.8
5	247.3	81.6	9.0	22.4
6	478.0	74.6	15.8	16.7
7	2389.1	1491.6	534.0	29.6
8	138.2	76.0	28.2	0.0
9	612.1	257.3	75.9	0.0

Sediment Detained in Ponds for Project:default

POND #	AREA (acres)	SEDIMENT DETAINED (tons/year)
201	77.2	22.9
207	209.2	48.1
208	257.9	15.6
209	367.4	33.1
210	173.4	18.5
212	764.7	133.2

Figure G-15 Screen capture of viewing the sediment budget



Forage Budget for Project: default

PASTURE #	AREA (acres)	TOTAL GRASS PRODUCTION (AUYs/year)	TOTAL BRUSH & FORB PRODUCTION (AUYs/year)	TOTAL GRASS GRAZED (AUYs/year)	TOTAL BRUSH & FORB GRAZED (AUYs/year)	AVERAGE CANOPY COVER	AVERAGE GROUND COVER
10	19.8	0.3	0.4	0.0	0.0	8.0%	13.9%
11	2213.7	35.7	45.9	15.9	3.3	7.3%	10.2%
12	676.0	33.6	11.2	13.7	0.5	7.0%	20.0%
13	352.9	7.2	6.9	3.1	0.5	7.1%	11.3%
14	8574.0	259.1	159.0	103.6	9.2	7.1%	14.4%
15	831.0	12.2	16.2	5.7	1.2	7.0%	9.4%
16	17.6	0.2	0.3	0.0	0.0	8.0%	11.0%
17	738.9	32.9	12.6	13.2	0.6	6.9%	18.7%
18	4156.6	109.5	73.6	40.1	4.1	6.7%	13.6%
19	1305.1	45.1	21.4	17.4	1.0	6.5%	16.0%
2	756.0	33.8	12.2	12.2	0.6	6.6%	19.8%
20	1265.0	14.2	25.2	5.8	1.6	7.1%	8.6%
21	1553.1	66.3	19.8	25.9	0.8	5.5%	17.4%
22	3020.9	70.0	53.8	24.0	2.6	6.8%	12.7%
23	98.4	3.2	1.4	1.3	0.1	5.7%	14.7%
24	854.4	16.1	17.1	7.6	1.2	7.3%	10.6%
25	2.6	0.0	0.1	0.0	0.0	8.0%	11.0%
3	1334.8	65.6	19.7	24.5	0.8	6.2%	20.6%
4	1871.4	90.1	31.4	38.8	1.6	7.0%	19.5%
5	247.3	12.3	4.1	4.8	0.2	7.0%	21.0%
6	478.0	21.5	8.2	10.5	0.5	7.0%	16.8%
7	2389.1	23.9	48.1	10.0	3.3	7.1%	8.2%
8	138.2	1.3	2.7	0.6	0.2	7.0%	8.0%
9	612.1	30.4	10.2	11.7	0.5	7.0%	21.0%

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Figure G-16 Screen capture of viewing the biomass budget

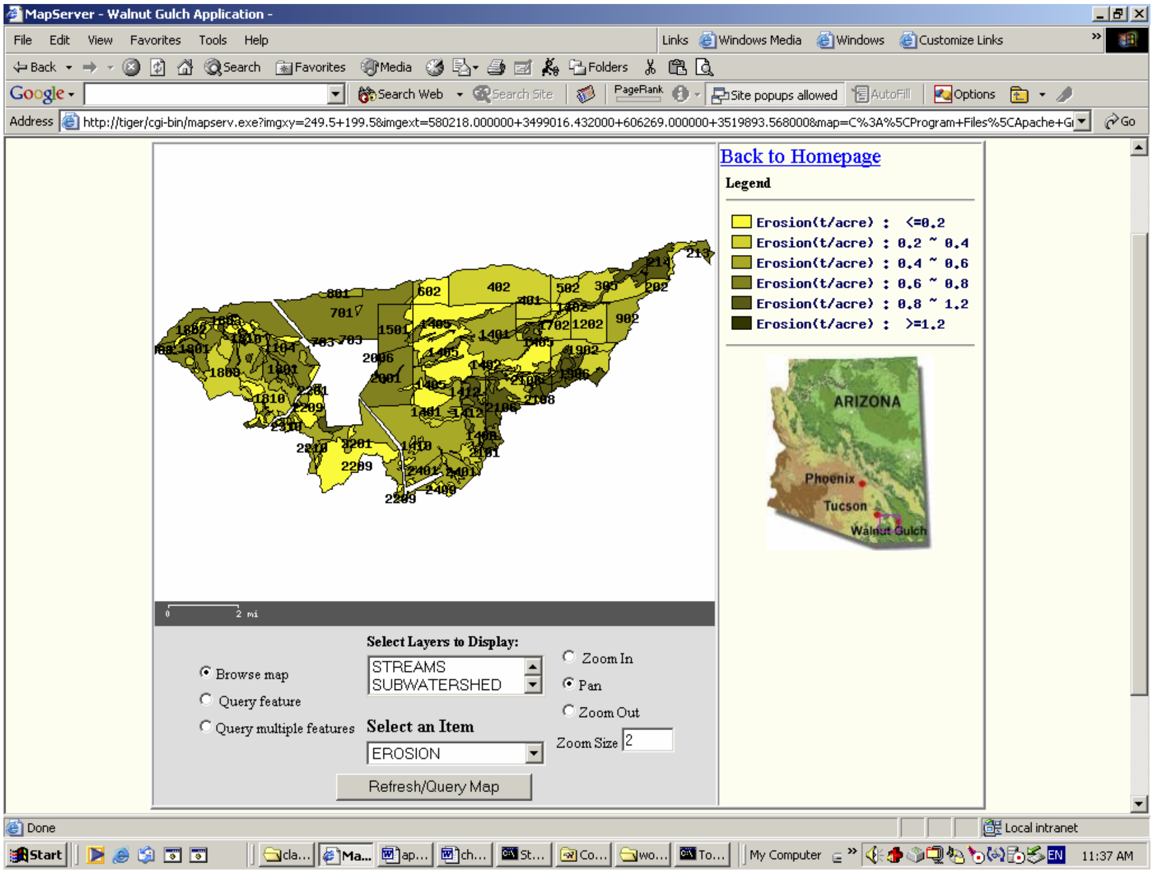

Figure G-17 Screen capture of viewing the erosion distribution map

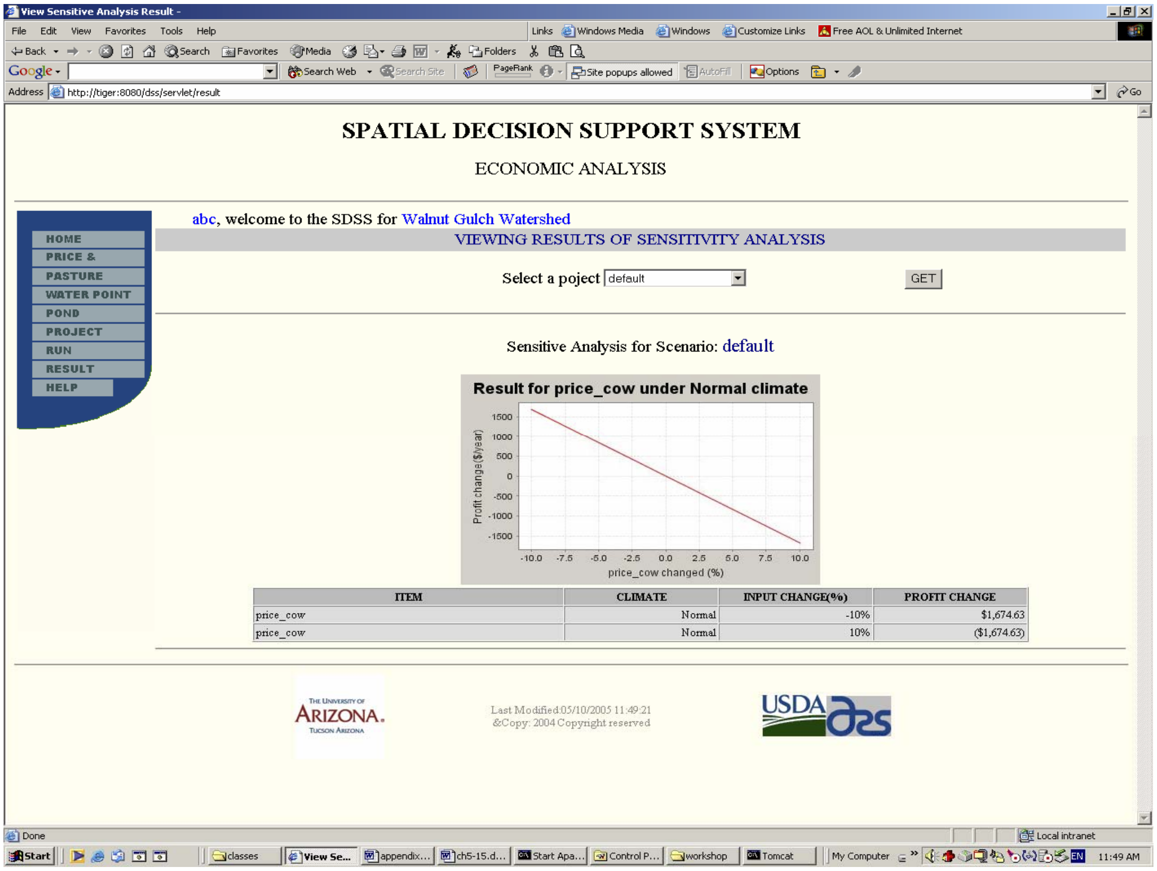

Figure G-18 Screen capture of viewing the sensitivity analysis result

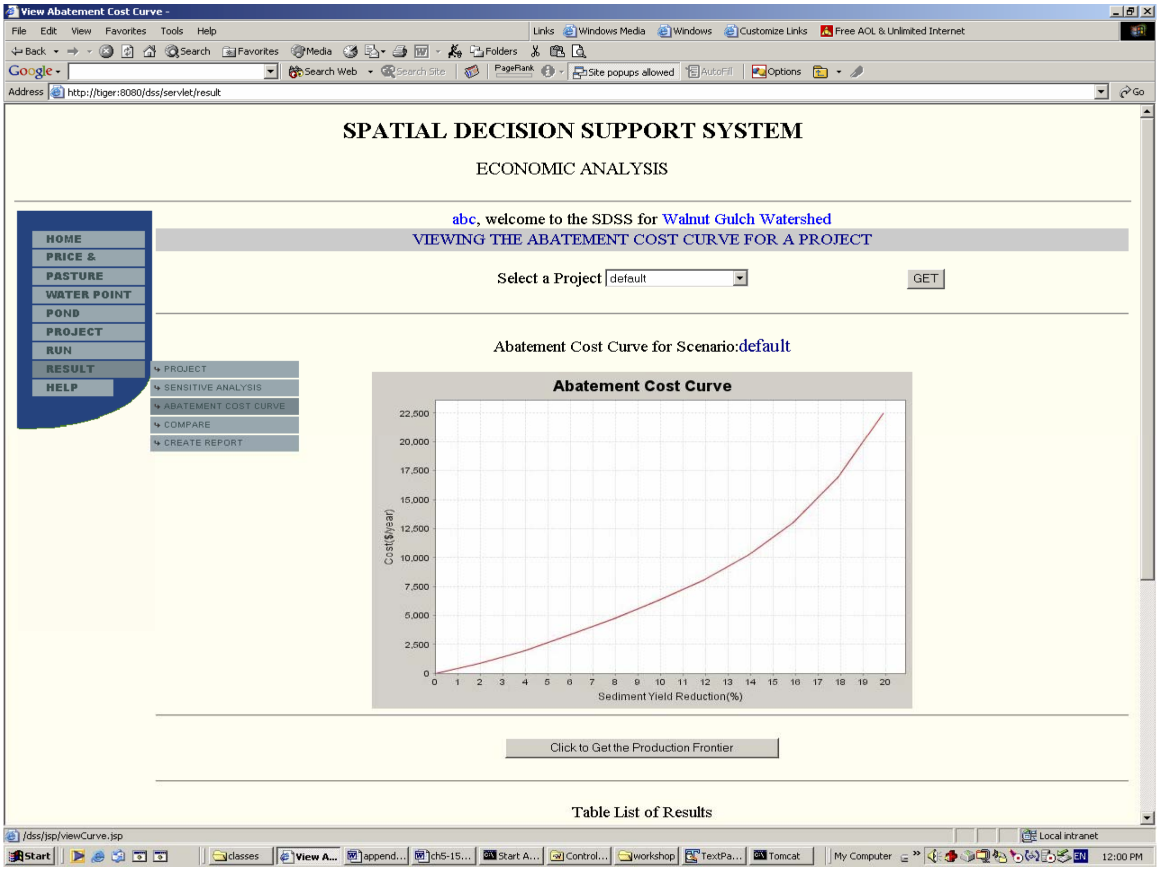

Figure G-19 Screen capture of viewing the abatement cost curve

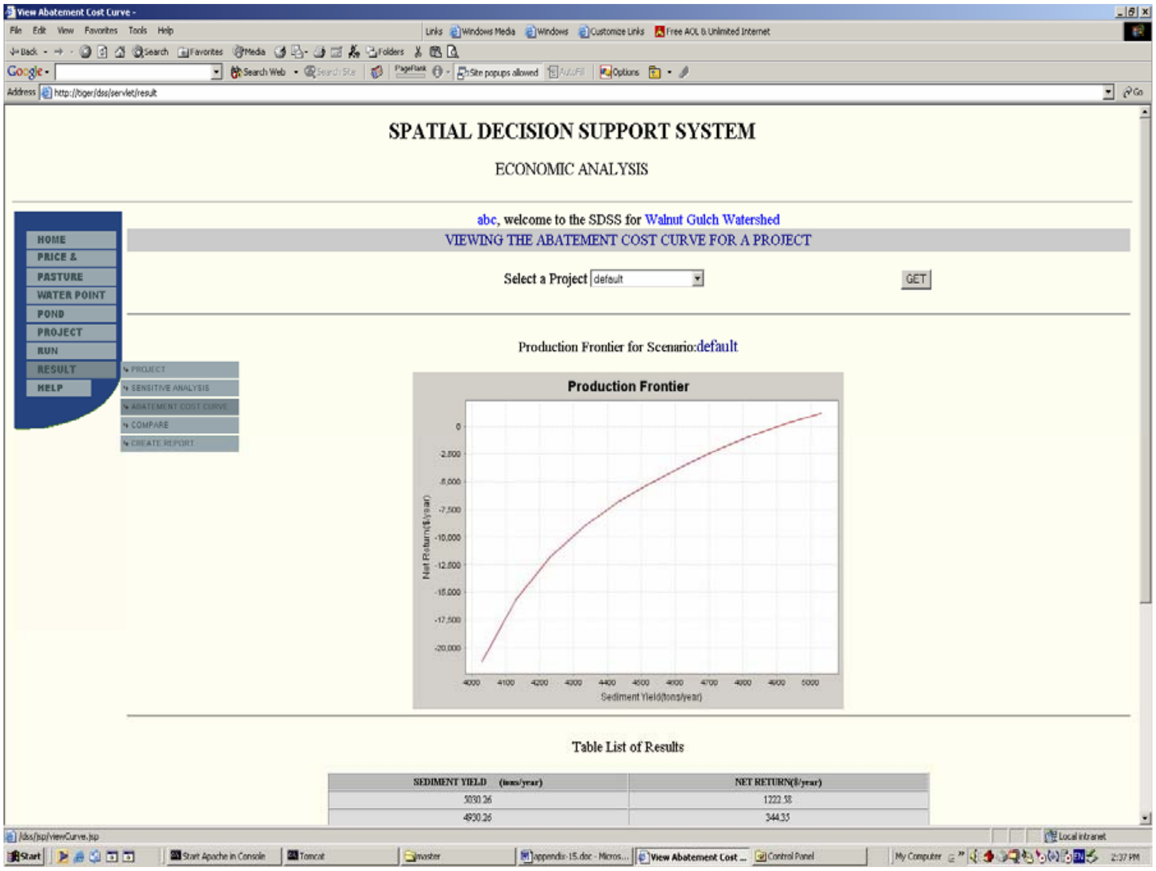

Figure G-20 Screen capture of viewing the production frontier

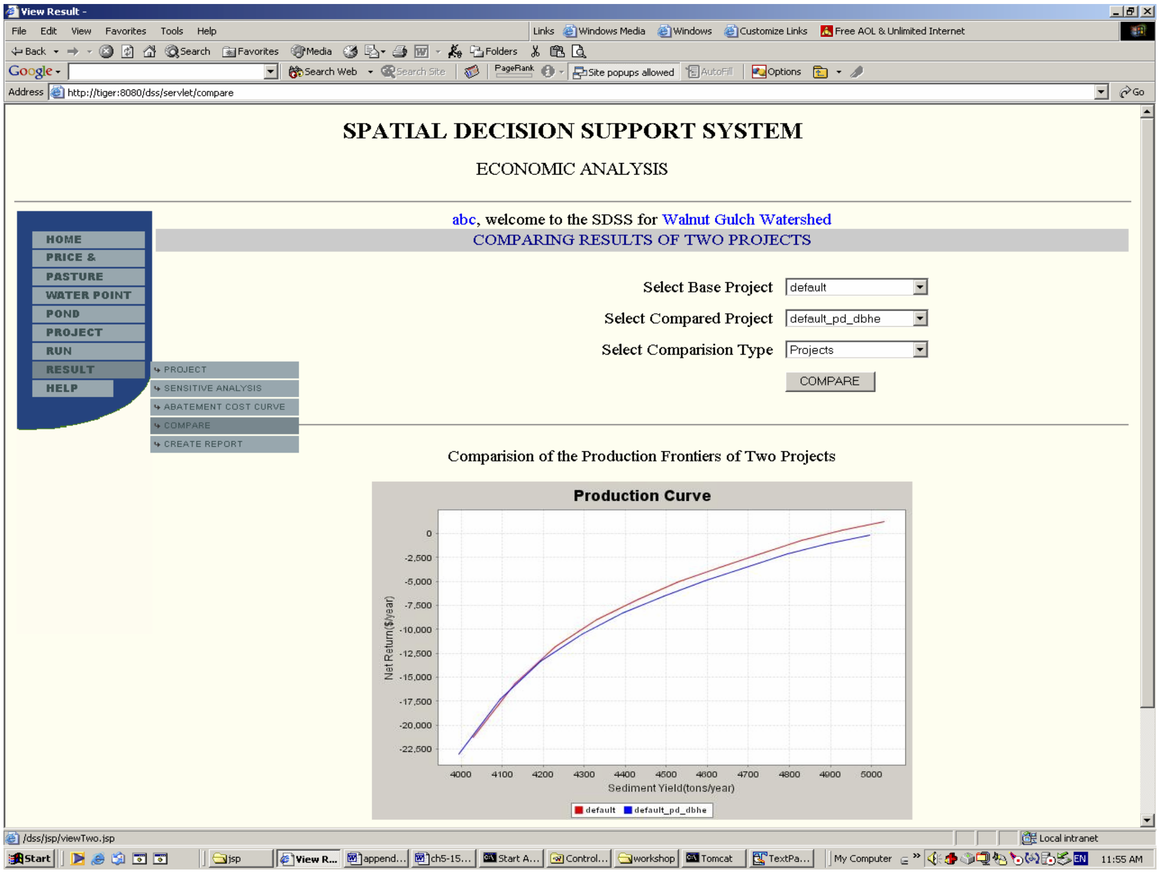

Figure G-21 Screen capture of comparing the production frontiers of two projects

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