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The Land and Water Integration Decision Support System

Isaac Wong
Environment Canada, isaac.wong@cc.gc.ca

Phil Fong
Environment Canada, phil.fong@cc.gc.ca

William G. Booty
Environment Canada, bill.booty@cc.gc.ca

Cathy Neilsen
Environment Canada, cathy.neilsen@cc.gc.ca

Glenn Benoy
Environment Canada, genn.benoy@cc.gc.ca

See next page for additional authors

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Authors

Isaac Wong, Phil Fong, William G. Booty, Cathy Neilsen, Glenn Benoy, and David A. Swayne

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Isaac Wong
Environment Canada
Isaac.Wong@ec.gc.ca

Phil Fong
Environment Canada
Phil.Fong@ec.gc.ca

William G. Booty
Environment Canada
Bill.Booty@ec.gc.ca

Cathy Nielsen
Environment Canada
Cathy.Nielsen@ec.gc.ca

Glenn Benoy
Environment Canada
Glenn.Benoy@ec.gc.ca

David A. Swayne
University of Guelph
dswayne@uoguelph.ca

ABSTRACT

Integration of data and component models describing habitat-based land use, non-point source pollutants transport, and water and soil quality forms the decision support development processes to assist policy makers in examining management options for dealing with the impacts of land use on water for agricultural issues in Canada. The land and water integration decision support system emphasizes on scale consistency, scenario gaming and testing, pollutant source tracing and optimal solutions. Examples of a watershed-based decision support system on water quality impact were presented as part of an assessment for the evaluation of best management practice options for future agricultural intensification scenario.

Keywords

environmental modelling, decision support system, integrated watershed assessment

INTRODUCTION

Agricultural activities such as animal farming, grazing, plowing, pesticide spraying, irrigation and fertilizer applications can cause non-point source or diffuse pollution. Nutrients and sediment are two of the main agricultural pollutants affecting water quality that result from these activities. Nutrients such as phosphorus and nitrogen are minerals that can be applied to enhance plant growth and crop production. When they are applied in excess of crop needs, the excess nutrients are often attached to soil particles that can be carried by overland water runoff from land into the aquatic ecosystems. The nutrients can cause excessive algae and aquatic plant growth in rivers and streams; cloud the water; reduce the amount of sunlight reaching aquatic plants; cover fish spawning areas and food supplies; greatly increase the costs of water treatment; reduce swimming and water recreation activities; create a bad smell; kill fish; and accelerate aging of rivers and lakes. Besides fisheries and recreation effects, these pollutants also have harmful effects on drinking water supplies and wildlife. Thus, there exists an important linkage between the land and the water. Environmental performance standards for floral and faunal communities in terrestrial ecosystems are based on assessments and forecasts of land cover and land use in agricultural regions. Performance standards for aquatic community structure in streams are based on assessments and forecasts of flow regime, sediment levels and nutrient concentrations. However, the physico-chemical condition of a stream is strongly affected by catchment characteristics, including land cover and land use, but also by basin shape, surficial geology and soil structure. Thus, land cover and land use patterns will have profound impacts on both water quantity and quality, and aquatic biodiversity.

Decision Support Systems (Alter, 1980) are computer-based interactive human-computer decision-making systems that assist policy makers in decision making processes. These systems utilize data and models to solve domain-specific problems and focus on effectiveness rather than efficiency in decision making processes. They are useful in better understanding this complex interaction between land and water. They also make informed resource management decisions and require the integration of scientific data, information, models and knowledge across multi-media (air, land and water), multi-disciplines and diverse landscapes (Wong et al., 2003).

In this paper, we discuss these key features of the land and water integration decision support system (LWIDSS), highlighting the decision support processes that include new integrated methodologies used, the feedback among component models, scenario testing and the optimal best management practices (BMP) with examples from the Raisin River watershed, located in eastern Ontario, Canada.

LAND AND WATER INTEGRATION DECISION SUPPORT SYSTEM METHODOLOGY

Modelling is an important asset of any environmental decision support system. With the high cost of full scale field work, modelling presents a cost effective approach to assess the impact of the environment. In the LWIDSS, the emphasis is on the terrestrial and aquatic models that are commonly used to assess agricultural impacts.

Dynamic landscape modelling helps decision makers assess the consequences of alternative management scenarios at the landscape scale. It simulates land use scenarios that are characterized by different assumptions about management practices. The results are in the form of GIS spatial layers that can be evaluated at the landscape level or can be fed into other component models such as non-point source pollutant models to evaluate the impact of land to water quality. This approach differs from other modelling efforts in that it does not confine itself to just one model or a given set of models. Rather, it provides an open architecture framework that accepts any component model within the system that can be linked to other component models in the causal chain, be it a dynamic landscape model for land use scenario creation or a non-point source pollutant model for sediment and nutrients assessment.

Land use scenarios are integrated with watershed hydrology models to develop flow, sediment and nutrient performance standards in streams to protect aquatic biodiversity. In addition to the scenario representing the present day (current), others are developed to explore different land use cases (e.g., agricultural intensification). Validated and calibrated hydrologic models use these scenarios to estimate water quantity and quality parameters. These parameters are then used to forecast aquatic biodiversity according to empirically-derived relationships between stream flow, sediment and nutrient regimes and biotic condition. Benthic algal and invertebrate communities, as well as fish communities, function as the biotic endpoints of streams and rivers to gauge ecosystem integrity.

Non-point source pollutant modelling in general can be a large and complex process requiring great quantities of input and generating vast amounts of output because of its nature of trying to simulate real-world processes. Dealing with such sums of data, both inputs and outputs, can be daunting to those who are trying to understand and extract knowledge and information from them. Not all modelling programs contain tools for visualizing the results, comparing multiple sets of results, performing post-analysis or managing/organizing the data from different model runs. Typically, after executing the models, different software are employed to look at the output and to perform further statistical analysis and these can be time consuming procedures by themselves. It is apparent that it would be very useful to have an integrated set of tools in a single software system that performs these tasks (Lam et al., 1998). This would make those doing modelling more productive by allowing them to examine the results in a more efficient manner. More time can be spent on modelling and less time on manipulating data to move it into software programs.

The LWIDSS addresses the issues of linking multi-media models at different geospatial scales. It provides interfaces that can accept, select, link and recalibrate discipline-specific component models. It can seek optimal solutions for best management practices such as buffer strip widths for sediment and nutrients reduction based on feedback of individual component models. The design of the LWIDSS has benefited from significant input from scientists, researchers, other end-users, system developers, modellers and Geographic Information System (GIS) specialists. Figure 1 illustrates the schematic diagram of the LWIDSS. At a glance, the LWIDSS offers a medium to integrate the data and information of the land and water by providing a number of necessary functionalities. The integration includes data, maps and models with user-friendly tools, including data input/output views, map input/output views, and modelling result views for interpretation, further analysis, conclusion and recommendation. The LWIDSS is designed as a framework and can be easily adapted to any watershed as portability is an important aspect of design consideration.

The LWIDSS is built around the concept of a management user interface to assist policy makers in their decision making. The technical users employ other tools to build model inputs, execute, and calibrate and validate the models; the technical aspect of the modelling process is beyond the scope of this paper. The friendly interface provides a platform for the management or policy makers to view the inputs and outputs of the system that the technical users have built. This will allow management to investigate the analytical results based on robust science built by the researchers. Key functionality includes mapping of the results, scenario gaming and key statistical analyses of the study area.

The LWIDSS design also calls for both temporal and spatial consistency among component models as the output from one model is used as input to another in a sequence of linked calculations. For example, the dynamic landscape model generates land use maps for various land use scenarios that can be used either in a single storm event non-point source pollutant model such as Agricultural Non-Point Source Pollutant Model (AGNPS) (Young et al., 1987), which is grid based or in a continuous time non-point source pollutant model such as Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), which is vector based.
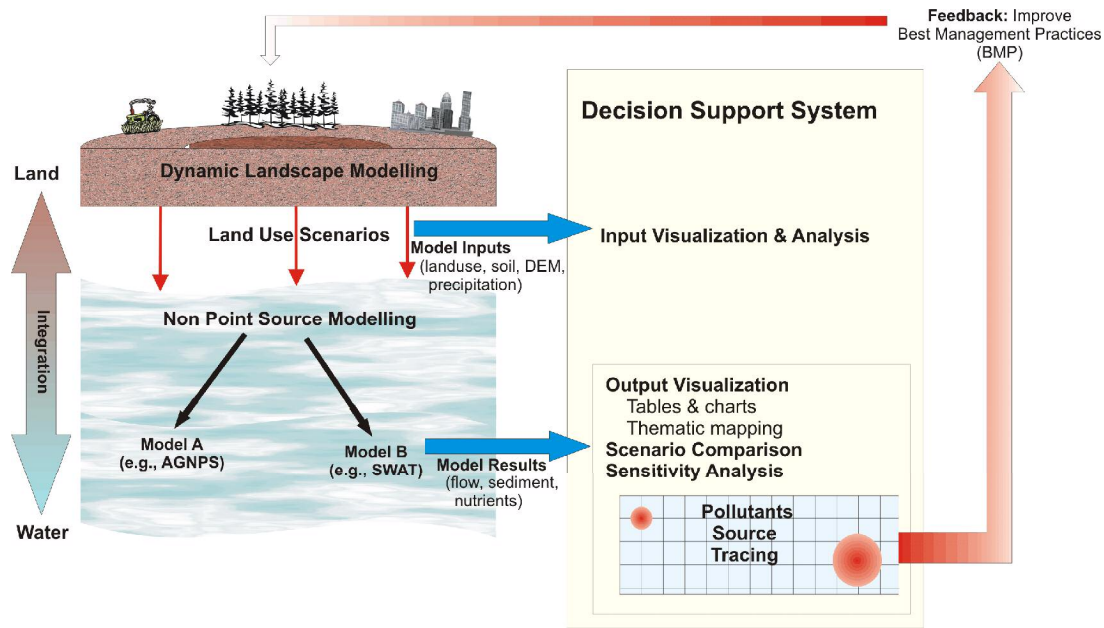
Figure 1: Schematic Diagram of the LWIDSS

A major requirement for policy makers is to use the LWIDSS to predict results, including evaluation of different scenarios on land and water and optimization of BMP. These should be obtained in a relatively short computational timeframe with a friendly user interface. Using the modelling approach to understand the non-point source pollutant problem is important for providing the assessment of the impacts of land-water integration. In addition, implementing a scenario gaming approach would allow decision makers an opportunity to understand the problem based on different possible scenarios and to make viable decisions to manage the problem more effectively and to minimize the impacts. The feedback among component models is critical to the whole integration process. Different models can complement each other with their strengths. For example, the AGNPS model excels in identifying pollutant "hot spots" and the SWAT model can take the information on the "hot spots" to further evaluate the optimal solution of BMP.

INTEGRATED ANALYSIS APPROACH

The integrated analysis approach will be described through an example which decision makers setting environmental policies could potentially face. The problem is to investigate a study area in Ontario, Canada to assess its current state in terms of aquatic ecosystem health and to forecast future conditions if agriculture practices need to be intensified because of increasing demands for crop production. For this paper, we identify the Raisin River Watershed, an agricultural watershed in Ontario, Canada as a pilot example for the development of the LWIDSS. It is selected to be the primary focus because agricultural activities can have an impact on the environment, in particular on the aquatic ecosystem. Current watershed conditions can be evaluated by gathering empirical data such as that done through water quality sampling. This usually involves sending people out into the field across the watershed at regular time intervals, collecting the water samples and analyzing the samples back at the laboratory. This method can be quite costly both in terms of time and money due to amount of labour and transportation and equipment requirements. In fact, it may not be feasible at all because of budget constraints or watershed size. Also, sites located in difficult to reach areas and poor weather can complicate the process. An alternate and more cost effective method is to make use of computer models to try to predict the water quality by simulating real-world physical processes occurring in nature (Leon et al., 2004). More specifically, some type of non-point source pollutant model is required to predict the level of pollutants (e.g., sediments) in the water system. Non-point source pollutant models such as AGNPS and SWAT, by themselves, are useful tools in aiding decision makers with setting up best management practices to improve water quality. But, when these models are coupled to a decision support system such as the LWIDSS, their effectiveness is enhanced. The LWIDSS provides value-added decision support functions to the models which otherwise may be lacking or deficient. In addition, it can make the overall decision support process easier and more productive for decision makers. We will explain the development of these decision support processes in detail next.

Decision Support Process 1: Review of Inputs

One of the first steps in any modelling work is to identify all of the input that is required by the model. In the case of watershed-based non-point source models, the physical characteristics of the watershed need to be described to the model for it to simulate the physical processes such as the hydrology. GIS map layers are used to define the soil texture, the land use and the surface topography (Digital Elevation Model) of the Raisin River Watershed. In addition, non-spatial data such as climate data including precipitation and temperature may also be necessary to simulate rainfall and evapotranspiration (transport of water from the surface to the air). Reviewing the input data of the models within the LWIDSS using multiple formats including maps, graphs and tables (Figure 2) is an important aspect in the overall decision support process. It allows policy makers an opportunity to check and possibly confirm whether or not the results produced from the model seem reasonable. Going back and examining the input data can also help to get some insight into why one is getting certain results when they may be expecting something different. The ability of the LWIDSS to overlay data from several GIS layers allows policy makers the ability to identify areas where data quality may be poor and thus require more attention. The ability to integrate data allows more valuable information to be generated.
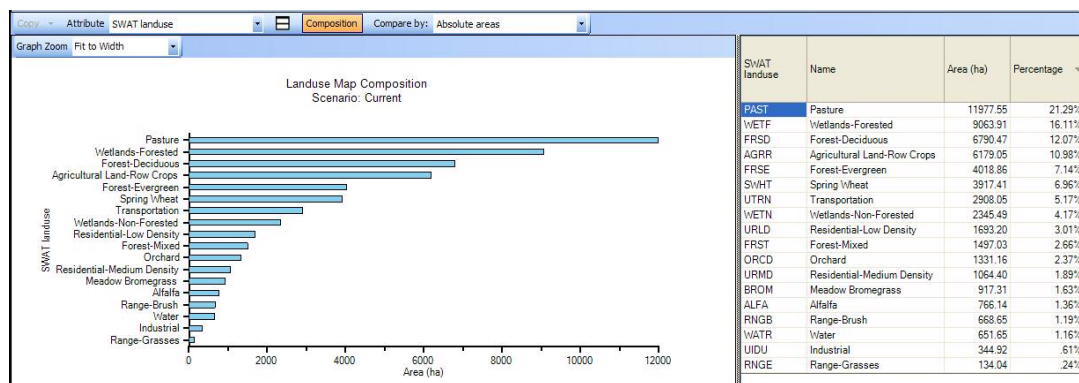

Figure 2: Reviewing model inputs in the LWIDSS. A chart and table of land use composition in the watershed is presented to identify the primary uses of the land.

Decision Support Process 2: Model Calibration and Validation

Non-point source models are run for the first time using current watershed conditions to assess the present situation (i.e., the current water quality). The accuracy of the model prediction is evaluated by comparing the results to known observation data (water quantity and quality). If the predictions are poor, then model variables are adjusted and the model is re-run until the predictions are satisfactory (unique watershed characteristics not reflected by the input data and data accuracy can cause the model to behave differently). This iterative process is referred to as model calibration and validation. The LWIDSS assists in this procedure by providing a platform for examining and visualizing the model outputs in a variety of different ways such as through graphs and tables and for comparing the outputs to the observation data. Model output from non-point source models are typically expressed as amounts of pollutants in the water (i.e., concentration). Results can be quickly accessed because they are organized by location within the watershed and by predicted parameter (e.g., stream flow and sediment). Results can also be filtered by time period and can be summarized to a broader timeframe. Predicted model outputs are compared to observations using plots of observations over predicted results (Figure 3) or using statistics such as regression coefficient *R* or Nash Sutcliffe coefficient (Nash and Sutcliffe, 1970) for quantitatively assessing the prediction accuracy.
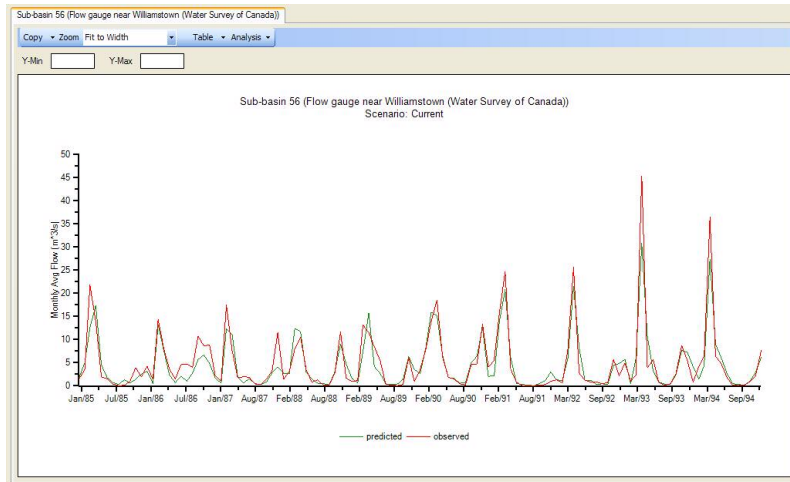
Figure 3: Reviewing model results in the LWIDSS for the purposes of model calibration. A plot of predicted flow (model) and observed flow (from a monitoring station) is examined to gauge prediction accuracy.

Decision Support Process 3: Scenario Gaming and Comparison

After a model is calibrated, it is now ready to be used for prediction in other situations, real or hypothetical. These are commonly referred to as scenarios. Suppose, in the future, there will be a need to increase the amount of agriculture to produce higher crop yields. The question that needs to be addressed is: how much of an impact will this agricultural intensification scenario have on the environment? The only feasible and cost effective means of arriving at an answer is through modelling. This scenario requires that a new hypothetical land use map be developed by experts using dynamic landscape models. This land use map will undoubtedly involve increasing the amount of land available for farming. The LWIDSS should provide the ability for policy makers to review and compare the land use maps from multiple scenarios (Figure 4), thus allowing them to provide comments and feedback to the landscape modellers. The non-point source model is run using the new agricultural land use map (and with the other input data staying constant). Policy makers then use the LWIDSS to analyze the results for the new agricultural intensification scenario and to also perform a scenario comparison (Figure 4) against the current scenario (present day land use map) through scenario gaming (Wong et al., 2007). This allows them to assess how much the pollution is predicted to increase when compared to the current environment and for them to plan the next course of action.
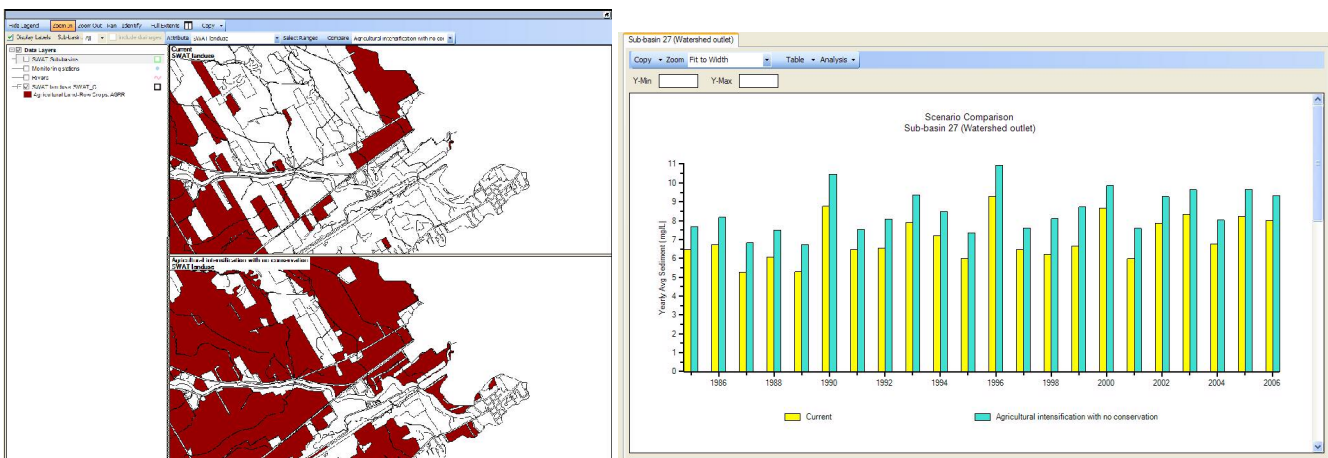

Figure 4: Reviewing model input (left) and results (right) in the LWIDSS for the purposes of scenario comparison. Left: Maps comparing land use for the two scenarios (top map: current; bottom map: agricultural intensification). Shaded areas are agricultural lands. Right: a chart comparing sediment concentrations predicted at the watershed outlet between two land use scenarios is examined to investigate the impact of land use to water quality.

Decision Support Process 4: Integrated Modelling Assessment

If the policy makers, after examining the model results, determine (based on current standards or guidelines) that the agricultural intensification scenario produces too much pollution, then what can be done to reduce the environmental impact (while still maintaining similar levels of agriculture needs)? An LWIDSS which has the capability of locating sources of pollutants through a source tracing analysis would be valuable to a policy maker in finding areas ("hot spots") whose pollution contribution exceeds a set threshold (Figure 5). These hot spots can then be targeted for change. They can be mapped and this information feeds back to the dynamic landscape model so that it uses this knowledge to update the existing agricultural land use map by applying best management practices to the hot spot areas. For example, filter strips could be added near water bodies to prevent agricultural pollutants from entering water resources. The non-point source model is then re-run and the results are compared to the previous set in the LWIDSS (Figure 5). If the amount of pollution reduction is unacceptable, then the set of target areas are updated and the whole feed back mechanism between the non-point source model and the landscape model is repeated until an "optimal" solution for best management practices is found.
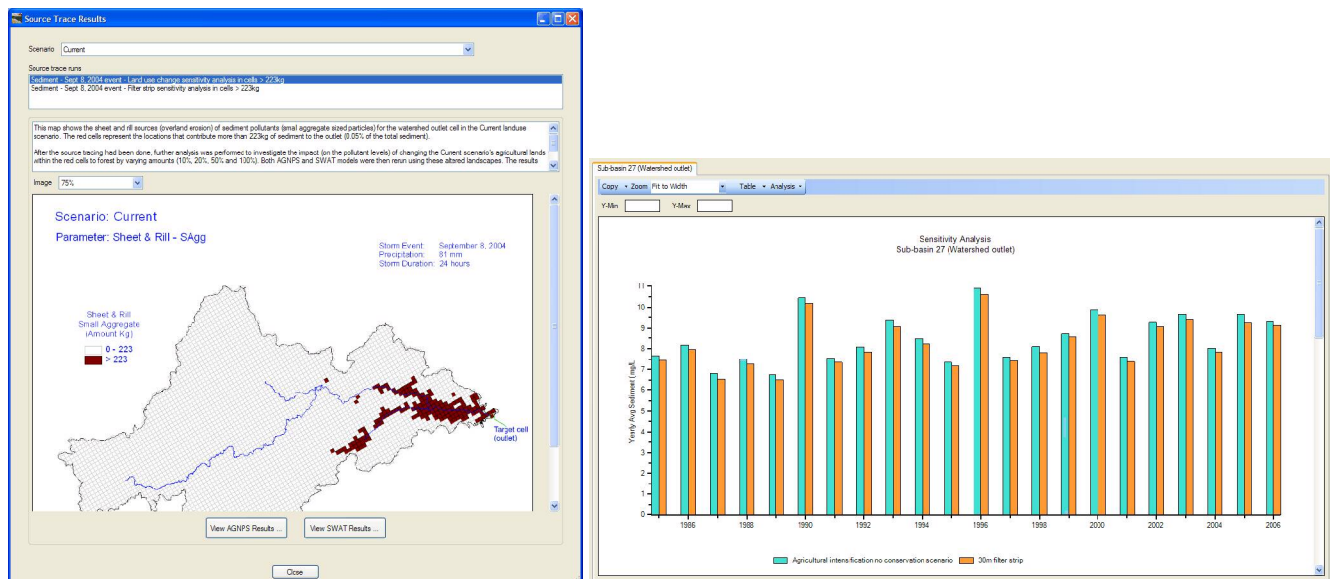

Figure 5: Reviewing results from source tracing analysis. Left: map displaying locations in the watershed that contribute higher amounts of sediment to the watershed outlet is analyzed to find potential target areas for best management practices. Right: a chart comparing sediment concentrations before and after best management practices (application of filter strips).

CONCLUSION

Designed for policy makers, the LWIDSS system is an effective analytical, planning and management tool to interpret and report modelling and scenario gaming results of the watershed-based modelling. Its framework can be used to determine the impact assessment of various land use scenarios on sediment and nutrients. The integrated decision support processes are captured in the LWIDSS and can be used for other similar watersheds if appropriate data is available. The results of the modelling and scenario gaming can be linked with other systems using a common data exchange interface.

The design of the LWIDSS facilitates integration of diverse information, ranging from various land use scenario map layers, to soil texture map layer, to Digital Elevation Model data, and to water quality data. It is also designed to provide an opportunity to query a variety of databases, to visualize spatial and/or temporal patterns, and to analyze model input data and output results using the DSS customized tools. Inherent to the LWIDSS architecture are relational databases with common design structures for data integration to be used in the modelling and scenario gaming framework. The use of modelling and scenario gaming will allow decision-makers to explore potential responses of land and water integration to hypothetical situations, i.e. to answer the "what-if" question. The feedback loop among the models is important for the policy makers to explore the best possible management options and the course of action for pollution control.

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