2008

Watershed Forest Management Information System (WFMIS)

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Repository Citation

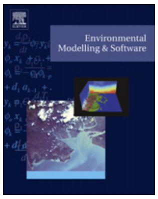
Zhang, Yanli and Barten, P. K., "Watershed Forest Management Information System (WFMIS)" (2008). *Faculty Publications*. 24.
https://scholarworks.sfasu.edu/spatialsci/24

Environmental Modelling & Software xxx (2008) 1–7

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft



Short communication

Watershed Forest Management Information System (WFMIS)

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ARTICLE INFO

Article history:
Received 13 February 2008
Received in revised form
9 October 2008
Accepted 10 October 2008
Available online xxx

Keywords:
Decision support system
GIS
Watershed management
Water resources
Zoning
Road
Forest harvest

ABSTRACT

Maintenance of a sustainable clean water supply is critical for our future. However, watershed degradation is a common phenomenon around the world that leads to poor water quality. In order to protect water resources, the Watershed Forest Management Information System (WFMIS), was developed as an extension of ArcGIS® and is described in this paper. There are three submodels to address nonpoint source pollution mitigation, road system management, and silvicultural operations, respectively. The Watershed Management Priority Indices (WMPI) is a zoning approach to prioritize critical areas for conservation and restoration management. It meets the critical need to spatially differentiate land cover and site characteristics within a watershed to quantify their relative influence on overall water quality. The Forest Road Evaluation System (FRES) is a module to evaluate road networks in order to develop preventive management strategies. The Harvest Schedule Review System (HSRS) is a module to analyze and evaluate multi-year and multi-unit forest harvesting to assist in the reduction of impact on water yield and associated changes in water quality. The WFMIS utilizes commonly available spatial data and has user friendly interfaces to assist foresters and planners to manage watersheds in an environmentally healthy way. Application examples of each submodel are presented.

Published by Elsevier Ltd.

Software availability

Name of software: Watershed Forest Management Information System (WFMIS)
Developed by: Yanli Zhang
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Tel.: +1 413 545 4358
Fax: +1 413 545 4853
Email: pkbarten@nrc.umass.edu
Availability: free at http://www.wetpartnership.org/software_downloads1.html
Available since: June 2006
Learning materials at: http://www.wetpartnership.org/softwareapps.html
Software required: ArcGIS 9.0 and up with Spatial Analyst extension.

1. Introduction

Life on earth depends on sustainable clean water supplies and systematic watershed management is critical to water resources protection. Watersheds are characterized by meteorological, surface water and groundwater, and physical and biological factors functioning within the context of natural and human disturbance regimes. The quantity, quality, and timing of streamflow within a watershed are influenced by these factors (McCammon et al., 1998; de la Crétaz and Barten, 2007). In order to improve the efficiency of limited conservation resources, the identification of critical areas and human activities that influence water resources is the primary objective of watershed analysis. Biophysical factors (soil, slope, land cover/use, etc.) and human impacts (road and timber harvest) should be considered systematically in forested watershed management. However, watershed models such as WAMView (Bottcher and Hiscock, 2001), WARMF (Weintraub et al., 2001), RESTORE (Lamy et al., 2002), EMDS (Girvetz and Shilling, 2003), WAWER (Girvetz and Shilling, 2003), and Mas et al. (2004) deforestation prediction model only deal with one aspect of watershed management. An integrated Management Information System (MIS), the Watershed Forest MIS (WFMIS), was therefore developed to facilitate watershed management to protect water resources. Development of the WMFIS began during the Source Water Stewardship Project (Barten and Ernst, 2004) and in consultation with the foresters at Quabbin reservoir (MA). It was designed as a general

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1364-8152/$ – see front matter Published by Elsevier Ltd.
doi:10.1016/j.envsoft.2008.10.006

Please cite this article in press as: Zhang, Y., Paul K. Barten, Watershed Forest Management Information System (WFMIS), Environ. Model. Softw. (2008), doi:10.1016/j.envsoft.2008.10.006

tool with three submodels to cover crucial aspects of forest watershed management for foresters, watershed management coordinators, or other water resources related managers. The Watershed Management Priority Indices (WMPI) submodel addresses the critical need to spatially differentiate land cover and site characteristics within a watershed to quantify their relative influence on overall water quality. The Forest Road Evaluation System (FRES) is used to evaluate existing road networks for maintenance planning. The Harvest Schedule Review System (HSRS) focuses on the analysis of cumulative timber harvesting with the goal of minimizing the adverse effects of forest harvesting on water resources such as water yield and quality.

The software was developed with Visual Basic as an extension for ArcGIS 9.0 and higher versions. Required input data include a digital elevation model (DEM), land cover, soils, stream networks, wetlands, roads, and other spatial data which are generally accessible through Geographic Information System (GIS) data clearinghouses at federal, state, city, and private levels. The following sections document the theories, functions, and application of the three submodels.

2. Watershed Management Priority Indices (WMPI)

Nonpoint source pollution from agriculture and urban and suburban development accounts for more than 60% of the impairment in U.S. waterways (US EPA, 1996). Land conservation and pollution prevention have proven to be cost effective strategies (NRC, 2000). However, with limited resources, where and how to start are critical questions in watershed management (Pullar and Springer, 2000). It is essential to evaluate and justify selection of crucial areas for environmental benefits (Rao et al., 2007). A GIS analysis approach, the WMPI, is designed to identify and rank place-based conservation, restoration, and stormwater management priorities to mitigate nonpoint source pollution (Barten and Ernst, 2004). The WMPI system can combine, analyze, and interpret multiple spatial factors efficiently in consideration of water quality protection and improvement. It is a multi-source GIS data modeling which can substantially improve the classification accuracy over techniques that use single source data by providing stronger correlation between geospatial data and features of interest (Rao et al., 2007). Within WMPI, for every physical factor (slope, soil permeability, etc.), each cell (spatial analysis unit of the watershed) is assigned a score to relatively estimate its influence on water resources. Then all the scores are weighted and added together using raster overlay. At the same time, cells are classified into three indices broadly representing the principal conditions of land: (1) forests and wetland, (2) agriculture and open space, and (3) residential, commercial, and industrial areas. These indices were named as conservation, restoration, and stormwater management priorities (CPI, RPI, and SMPI), respectively. The WMPI analysis flow chart is shown in Fig. 1. Additionally, optional layers such as public water supply restriction areas, aquifers, or other spatial factors that are important for local water resources can be included. The final result is identification of the crucial areas (those with the highest scores) within land falling in the three index types: conservation, restoration, and stormwater management.

Four consecutive user interfaces were designed (Fig. 2) to facilitate the usage of the model. The interfaces' functions are input data selection, priority index setting, parameter setting, and output format selection. As different watersheds may have different land use/cover categories, the system will dynamically track the input land use/cover categories and set up the second interface. Input spatial data include but are not limited to DEM, land use/cover, soils, and water bodies. Users can change inputs and their weights, adjust priority indices, and use different parameters for the analysis according to local requirements. The WMPI tool was designed to be generic to allow wide use.

The results of a WMPI analysis highlight critical areas of the watershed for conservation and restoration. Each Priority Index (PI) is displayed using a different color (CPI with green, RPI with orange, and SMPI with red). The results are presented as a graduated legend with darker colors indicating a higher value or higher priority for conservation, restoration, or stormwater management.

Dry Run Creek watershed (Cedar Falls, IA) was used to demonstrate an application of WMPI. This watershed has an area of 61.5 km^2 (61.3% agricultural land, 21.6% developed area, and 17.0% natural area). All of the original spatial data, such as the USGS 30-m resolution DEM, 2002 land cover, road network, the Soil Survey Geographic (SSURGO) data, rivers, wetlands, and lakes, were collected from Iowa Department of Natural Resources (DNR). The results (Fig. 3) indicate that management priorities could be given to those areas with the highest scores after field verification and assessment, for example, a conservation easement for an area with high CPI value and a stormwater retention pond for an area with high SMPI value. The Dry Run Creek watershed coordinator has used WMPI to identify hot spots to build stormwater retention ponds and to restore stream banks. It also has been used to demonstrate watershed analysis in local watershed management meetings involving a diversity of stakeholders.

3. Forest Road Evaluation System (FRES)

Forest roads provide basic accessibility for people to enjoy and manage natural resources. However, they are a primary source of sediment (Wemple et al., 2001). As noted by the USDA Forest Service (2000), not all roads have the same effects on watersheds. Variation is great and differentiation between high impact and low impact roads is an important analytical challenge. This challenge led to the development of the Forest Road Evaluation System (FRES). The FRES assists foresters in finding potential problems within existing road networks to develop an effective maintenance plan to protect water resources.

In the FRES, factors such as road slope, cutslope, fillslope, stream crossing location, and distance to water body are analyzed when considering road related erosion and sediment loading. Because the accuracy of slope calculation is determined by spatial resolution (Longley et al., 2001) and in consideration of common forest road width and the availability of DEM data, 5-m resolution DEM data were used in the design and testing of the FRES. The 3 × 3 window algorithm (8 neighboring cells' elevation are used in calculating the central cell's slope) is the most common method of calculating slope. However, when calculating road slope, the cells neighboring the road will incorrectly influence the calculation of road slope, especially when the road is parallel to contour lines. In order to avoid this problem, an intermediate road elevation dataset (only cells reflecting road segments have elevation values) was created to use in the general slope calculation algorithm. This approach was validated by comparing calculation results with field measurements at typical road segments in the Quabbin Forest. The elevation difference between road surface and its neighboring cells is used to reflect cutslope or fillslope and Fig. 4 shows the calculation flow chart. Stream crossing locations are calculated through the interception of roads and streams. Buffers and intersections are used to find roads near water bodies.

Fig. 5 shows the test results (road slope, cutslope, and fillslope) for a section of roads in the Quabbin Forest. Red is used to symbolize road slope, the darker the color, the steeper the slope is. Cutslope and fillslope are shown with green and purple, respectively. Again, the darker the color, the greater the cut height or fill depth is. Table 1 shows the statistical summary from the FRES analysis. This information and output maps form a useful database

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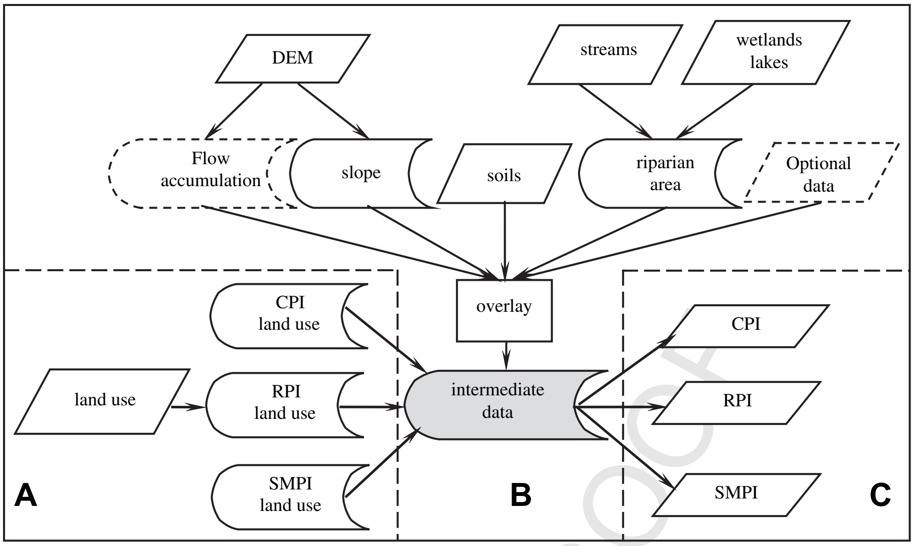
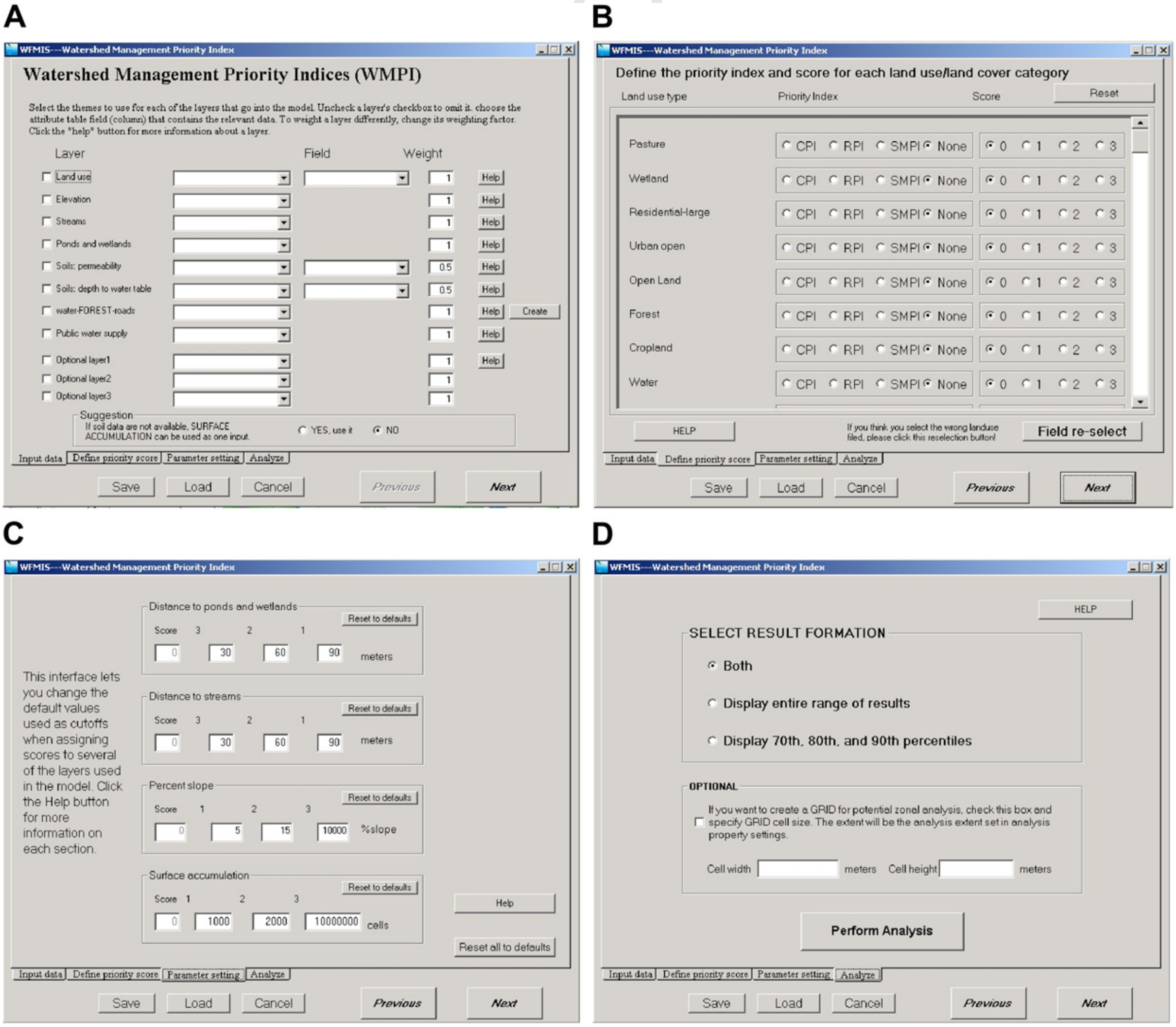


Fig. 1. Flow chart of Watershed Management Priority Indices (WMPI).

for watershed managers and foresters to manage the existing road system in a way that can minimize sediment loading, water treatment costs, and adverse environmental effects on aquatic ecosystems.

4. Harvest Schedule Review System (HSRS)

Timber harvesting changes headwater stream characteristics such as the quantity and timing of base flow and storm flow,



A

Watershed Management Priority Indices (WMPI)

Select the themes to use for each of the layers that go into the model. Uncheck a layer's checkbox to omit it. choose the attribute table field (column) that contains the relevant data. To weight a layer differently, change its weighting factor. Click the "help" button for more information about a layer.

Layer	Weight
☐ Land use	1
☐ Elevation	1
☐ Streams	1
☐ Ponds and wetlands	1
☐ Soils: permeability	0.5
☐ Soils: depth to water table	0.5
☐ water-FOREST-roads	1
☐ Public water supply	1
☐ Optional layer1	1
☐ Optional layer2	1
☐ Optional layer3	1

Suggestion
If soil data are not available, SURFACE ACCUMULATION can be used as one input.
○ YES, use it ● NO

B

Define the priority index and score for each land use/land cover category

Land use type	Priority Index	Score
Pasture	○ CPI ○ RPI ○ SMPI ● None	● 0 ○ 1 ○ 2 ○ 3
Wetland	○ CPI ○ RPI ○ SMPI ● None	● 0 ○ 1 ○ 2 ○ 3
Residential-large	○ CPI ○ RPI ○ SMPI ● None	● 0 ○ 1 ○ 2 ○ 3
Urban open	○ CPI ○ RPI ○ SMPI ● None	● 0 ○ 1 ○ 2 ○ 3
Open Land	○ CPI ○ RPI ○ SMPI ● None	● 0 ○ 1 ○ 2 ○ 3
Forest	○ CPI ○ RPI ○ SMPI ● None	● 0 ○ 1 ○ 2 ○ 3
Cropland	○ CPI ○ RPI ○ SMPI ● None	● 0 ○ 1 ○ 2 ○ 3
Water	○ CPI ○ RPI ○ SMPI ● None	● 0 ○ 1 ○ 2 ○ 3

If you think you select the wrong landuse filed, please click this reselection button!

C

This interface lets you change the default values used as cutoffs when assigning scores to several of the layers used in the model. Click the Help button for more information on each section.

Distance to ponds and wetlands
Score 3 2 1
0 30 60 90 meters

Distance to streams
Score 3 2 1
0 30 60 90 meters

Percent slope
Score 1 2 3
0 5 15 10000 %slope

Surface accumulation
Score 1 2 3
0 1000 2000 10000000 cells

D

SELECT RESULT FORMATION
● Both
○ Display entire range of results
○ Display 70th, 80th, and 90th percentiles

OPTIONAL
☐ If you want to create a GRID for potential zonal analysis, check this box and specify GRID cell size. The extent will be the analysis extent set in analysis property settings.
Cell width meters Cell height meters

Fig. 2. Interfaces of Watershed Management Priority Indices (WMPI).

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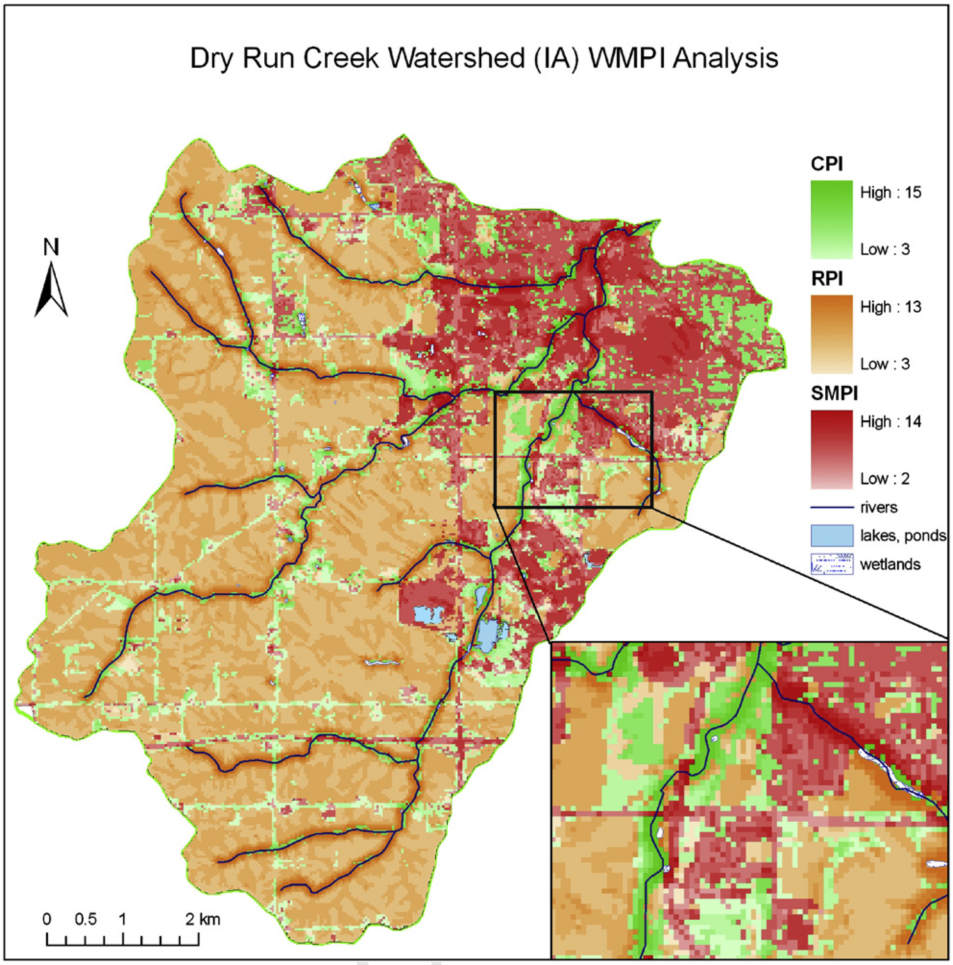

Fig. 3. Test of Watershed Management Priority Indices (WMPI) at Dry Run Creek Watershed (Cedar Falls, IA).

concentration of sediment and dissolved nutrients, water temperature, and the stability of the stream channels ~~(Zhang, 2006, 2008~~). For a given watershed, suppose that precipitation, water storage, and water leakage will not change much from year to year under normal conditions. Timber harvesting generally means less transpiration and canopy interception (Hornbeck et al., 1997). Evapotranspiration will be reduced and, in consequence, water yield will increase. Kovner (1956) analyzed a case in Coweeta (North Carolina) and demonstrated that streamflow increases were independent of the annual precipitation after harvesting. Lull and Reinhart (1967) also concluded that below normal or above normal annual precipitation after forest removal did not have a pronounced effect on water yield increases. These historical studies confirmed that precipitation variance does not affect water yield increase caused by forest harvesting. Along with increased water yield, wetter soil, nutrient mobilization, decreased water quality, and increased channel erosion will occur. The relationship between timber harvesting and water yield increase, and the long-term change of this increase, have been studied extensively. Previous studies (Kovner, 1956; Lull and Reinhart, 1967; Douglas and Swank, 1972; Bosch and Hewlett, 1982; Douglas, 1983; Verry, 1986; Hornbeck et al., 1997; Swank et al., 2001; Hornbeck and Kochenderfer, 2004) demonstrated a mathematical relationship between forest harvesting and corresponding water yield increase. Generally the water yield increase will disappear after 5–20 years if the forest is fully recovered. Based on a careful literature review (Lull and Reinhart, 1967; Douglas and Swank, 1972; Hornbeck et al., 1997; Swank et al., 2001), a "disturbance threshold" theory was proposed to study the influence of forest harvesting on water yield. This threshold is applied as either the proportion of treated area or the proportion of biomass removal in the watershed. Below this threshold, water resources are considered as not being significantly influenced by forest harvest.

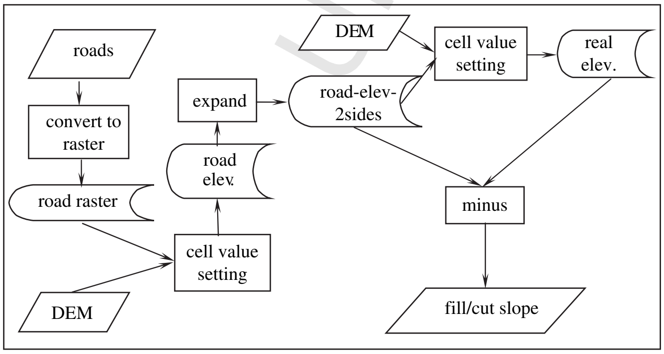

Fig. 4. Cutslope and fillslope calculation flow chart.

In order to mathematically evaluate accumulated forest harvesting effect, a disturbance index (R) is used to consider multi-year harvesting, multi-harvesting units, and regrowth after harvesting.

$$R = \frac{\sum_{i}^{N}(X_i Y_i A_i)}{\text{Total Watershed Area}} \tag{1}$$

where N is the number of management units, for each management unit (i), X_i is recovery time index ($0 \le X \le 1$) which accounts for tree

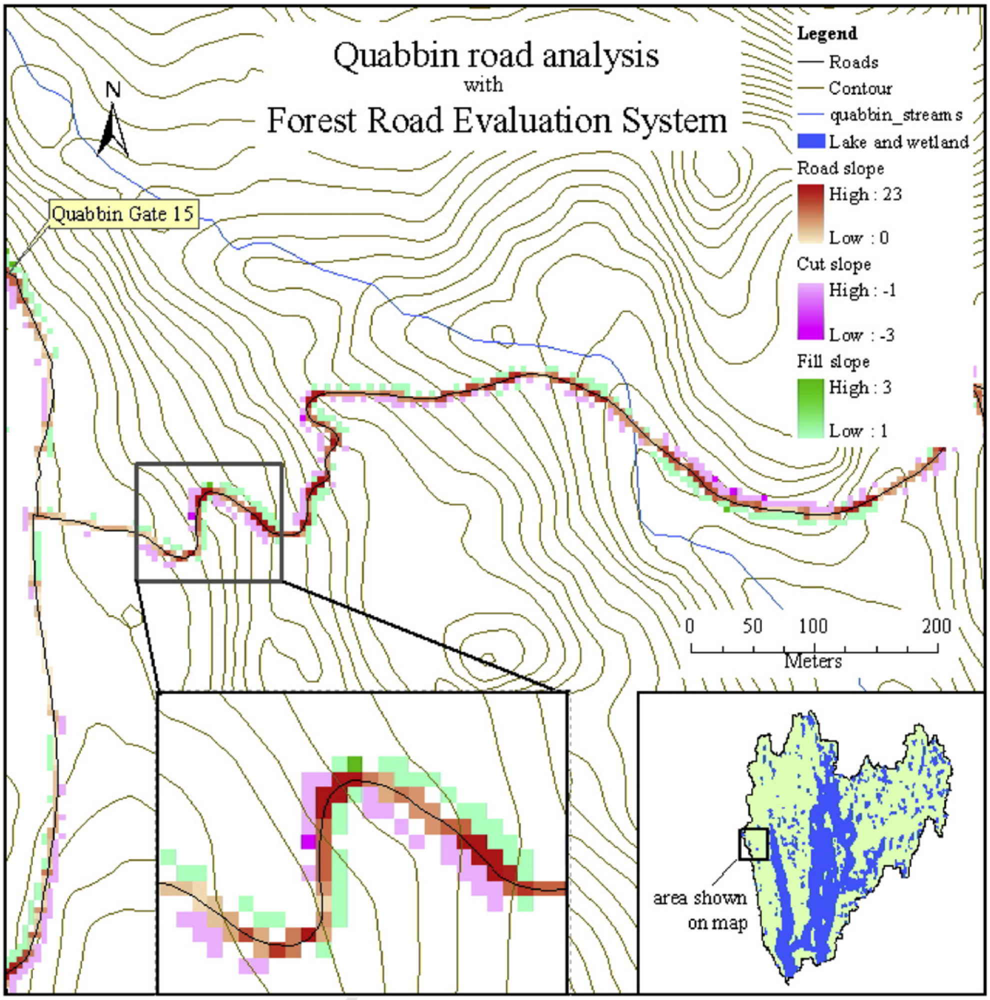

Fig. 5. Quabbin road analysis with Forest Road Evaluation System (FRES).

growth after harvest, Y_i is treatment index ($0 \le Y \le 1$) which is the percentage of the area cut or percentage of biomass removal ~~(Zhang, 2006, 2008~~). Y_i represents harvest type, whether it is clear cutting, strip cutting, or thinning. A_i is the area of the management unit within the subwatershed.

Based on Eq. (1), the HSRS interface (Fig. 6) was designed to facilitate development of retrospective and future harvest plan analyses. The recovery time index (X_i) is derived from the management unit's harvest year and full recovery period. The treatment index (Y_i) is the value set by the user in the harvest layer's attribute table according to actual harvest method. The retrospective analysis uses historical harvest data to calculate R for each watershed (block) of interest for past and current years. This can help foresters to accurately quantify the effects of earlier cutting. Foresters also could combine this result with past water quality/quantity records to establish a local disturbance threshold. Future harvest plan analysis is based on historical harvest data (to establish initial conditions) and future harvest plan data to calculate the potential R for each watershed. This can help foresters to predict the potential impact of a given harvest plan on water quality/quantity, and then make necessary harvest plan changes as needed to protect water resources.

The HSRS was applied with forest harvest data from the Quabbin Forest and Fig. 7 shows the analysis result. Users of the HSRS need to set the disturbance threshold and recovery time based on the local situation (climate, tree species, topography, soil, etc.) as forest recovery is influenced by these factors. The watersheds with an R-value above the user specified threshold are in white, alerting planners and foresters to watersheds where changes may be necessary. For example, delaying a proposed harvest by 2 or 3 years could allow adequate time for regeneration on earlier harvest units to ensure the watershed's R-value stays below the threshold. Similarly, shifting the harvest unit to an adjacent subwatershed or altering harvest area can help too.

Table 1
Roads management information generated with FRES (Quabbin Forest roads near Pelham, MA).

Total length	64,332 m
Steam crossings	32
Roads within 30 m of water	7243 m
Cutslope	1-m cut: 21,782 m 2-m cut: 3357 m 3-m cut: 135 m
Fillslope	1-m fill: 23,442 m 2-m fill: 2409 m 3-m fill: 118 m
Road slope	$0 < \text{slope} \le 5\%$: 46,760 m (73%) $5\% < \text{slope} \le 10\%$: 12,391 m (19%) $10\% < \text{slope} \le 15\%$: 1766 m (3%) $15\% < \text{slope}$: 182 m (0.3%)

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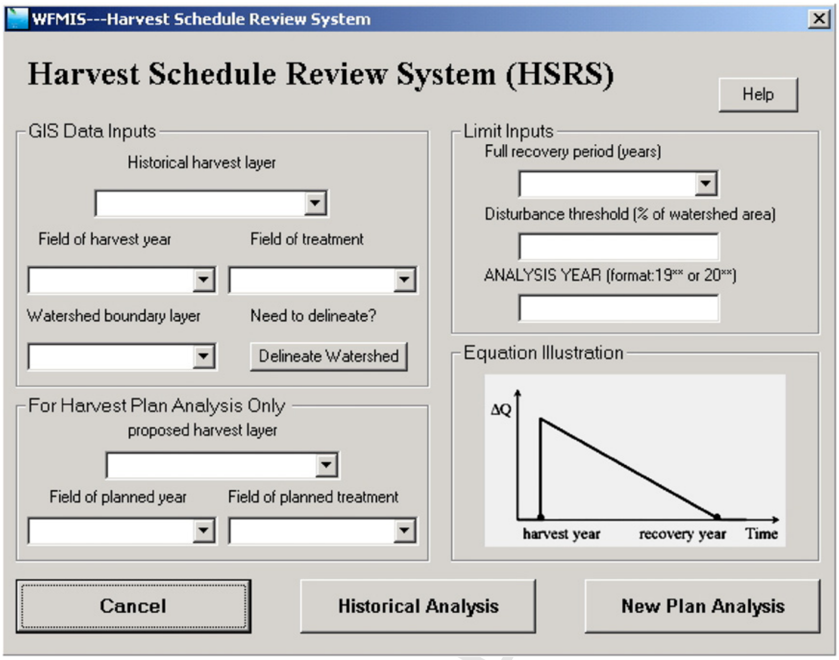

Fig. 6. Interface of Harvest Schedule Review System (HSRS).

5. Summary

The theories, main functions, and example applications of the newly developed WFMIS are reported to introduce this tool to the research community and foresters for protection of water resources through watershed management. Within the system, the WMPI focuses on prioritizing land for conservation and restoration, the FRES evaluates road networks to optimize management strategies, and the HSRS analyzes the spatial distribution and silvicultural method of timber harvesting in consideration of their impacts on water resources. As water resources protection is a complex issue and includes many aspects, the main effort for the future version of this software would be covering more of those aspects, such as soil erosion prediction, road network planning, and wildlife habitat influence.

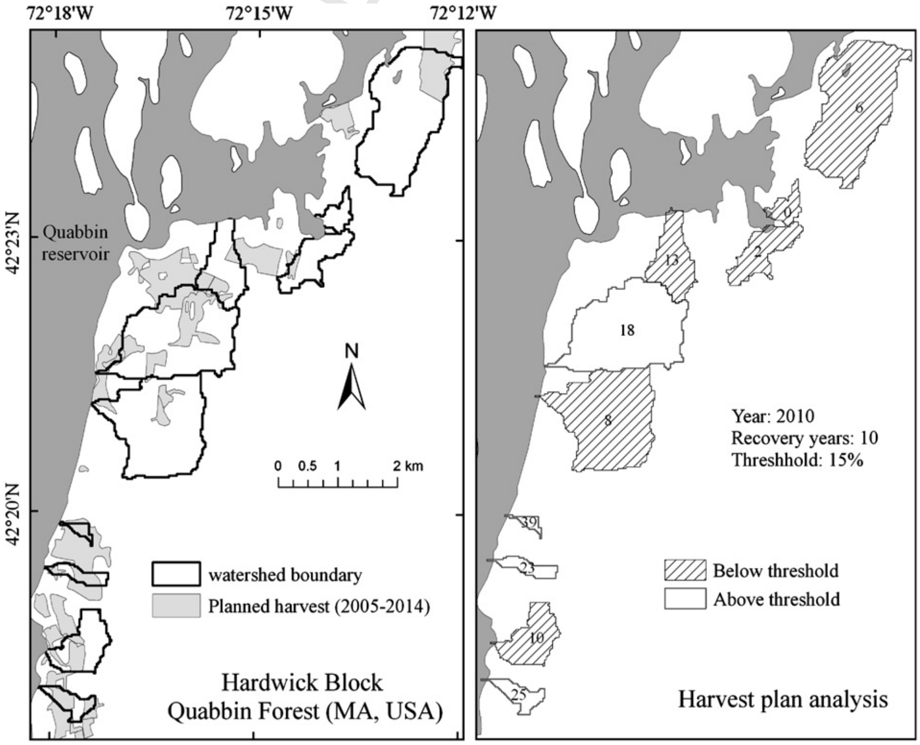

Fig. 7. Test of Harvest Schedule Review System (HSRS) with Hardwick Block (Quabbin Forest, MA) harvest data.

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Neitsch et al., 2005; Swank et al., 1988; US EPA, 2000; Zhang et al., 2008.

Acknowledgments

The authors gratefully acknowledge the funding provided by the USDA Forest Service, Northeastern Area, State and Private Forestry (Albert H. Todd, Martina Hoppe, Robin Morgan, and Kathryn P. Maloney), and the US EPA, Office of Water (Deborah Gutenson). Also we express our appreciation to David B. Kittredge Jr., Mark S. Lindhult, Charles M. Schweik, Avril L. de la Cretaz, Thom Kyker-Snowman, Helen Johnson, Steve Ward, and David Kimball for their valuable support and suggestions. The authors would like to thank John DeGroote and three other anonymous reviewers for helping edit this paper.

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