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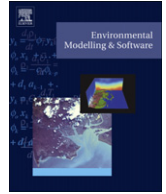
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Short communication

Watershed Forest Management Information System (WFMIS)

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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.

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Software availability

Name of software: Watershed Forest Management Information System (WFMIS)

Developed by: Yanli Zhang

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Tel.: +1 413 545 4358

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Email: pkbarten@nrc.umass.eduAvailability: 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 Cr  taz 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 WFMIS 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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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 clearing-houses 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 km² (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

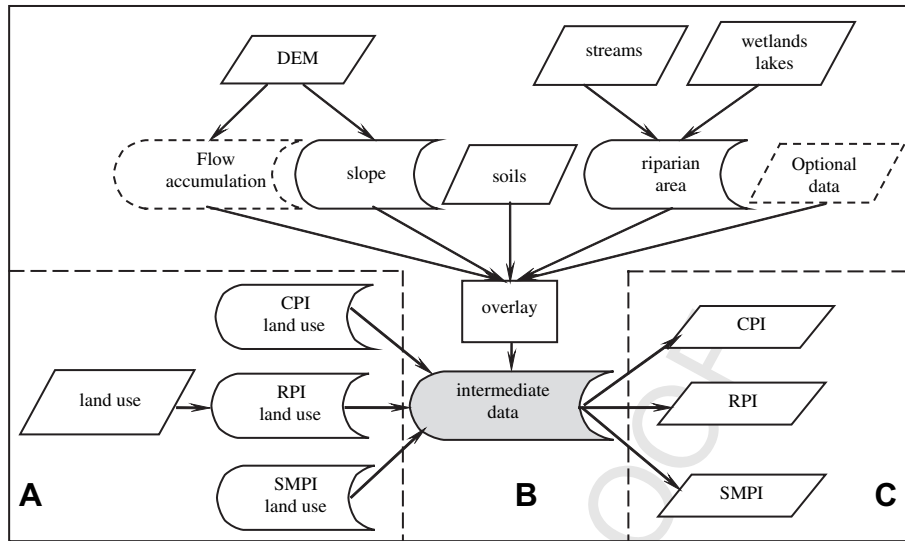


Fig. 1. Flow chart of Watershed Management Priority Indices (WMPI).

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,

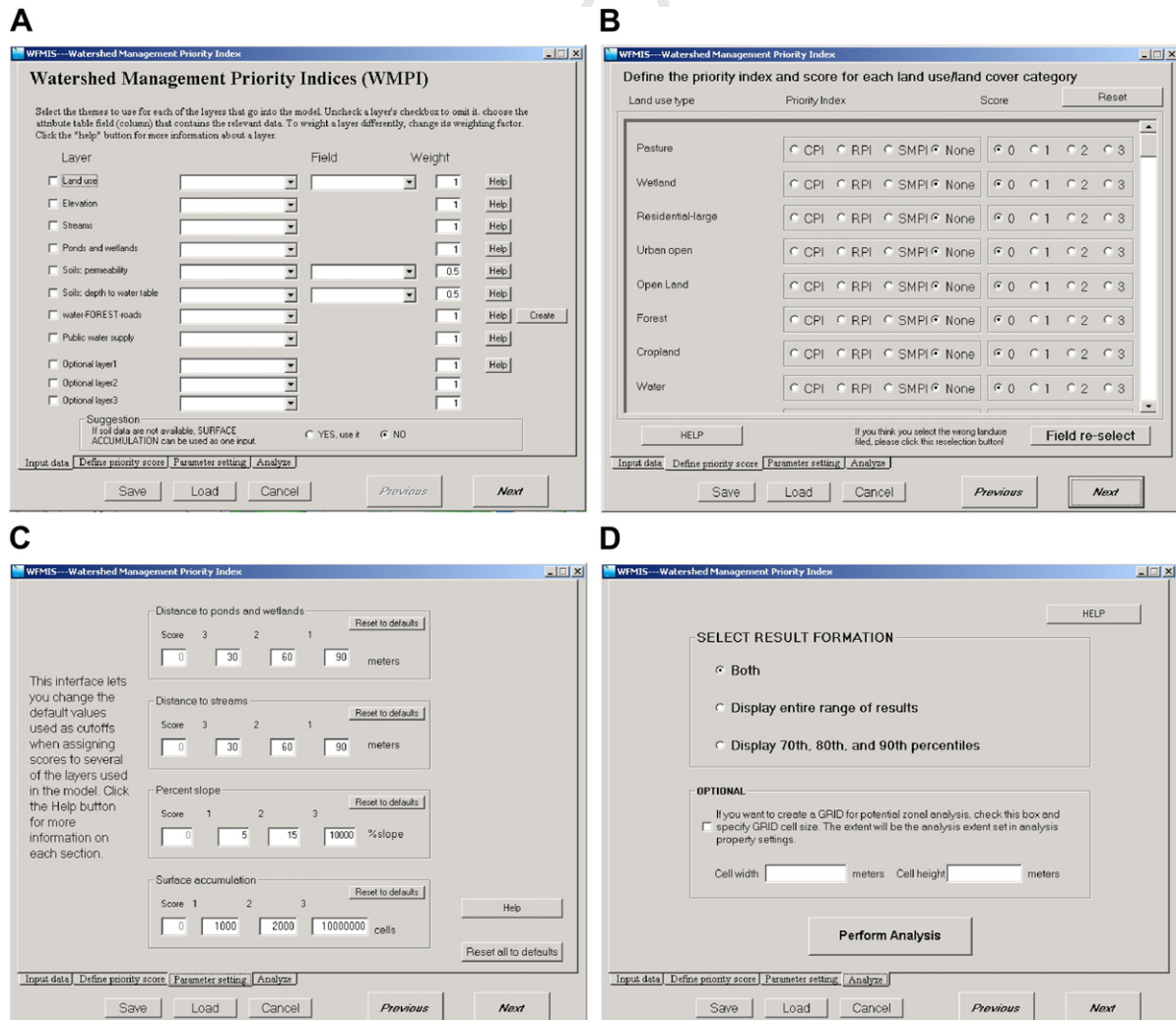


Fig. 2. Interfaces of Watershed Management Priority Indices (WMPI).

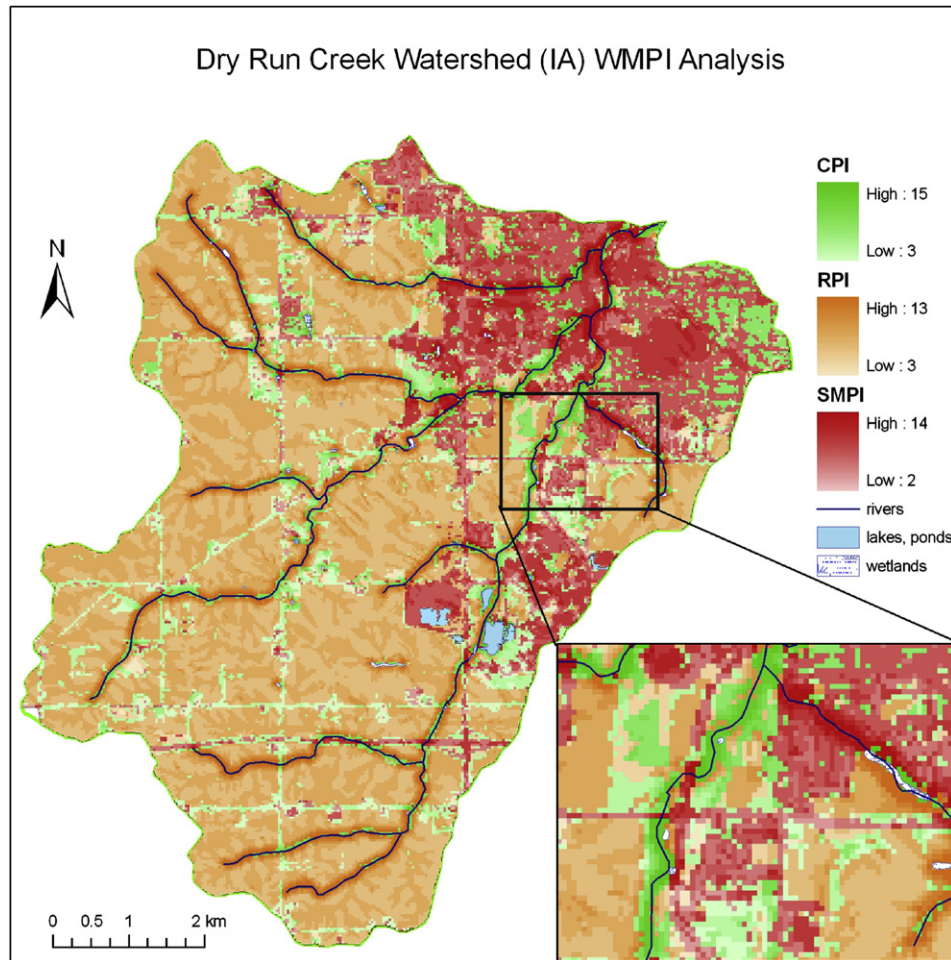


Fig. 3. Test of Watershed Management Priority Indices (WMPI) at Dry Run Creek Watershed (Cedar Falls, IA).

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.

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.

$$R = \frac{\sum_i^N (X_i Y_i A_i)}{\text{Total Watershed Area}} \quad (1)$$

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

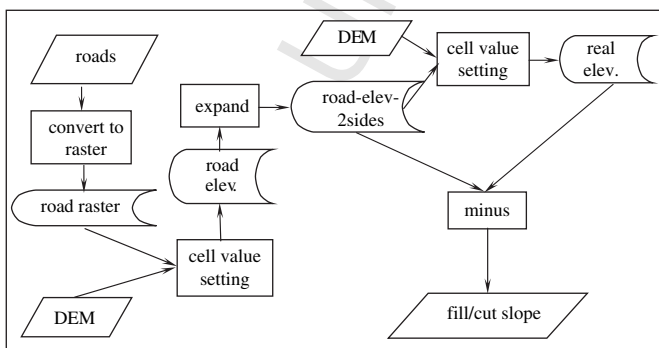


Fig. 4. Cutslope and fillslope calculation flow chart.

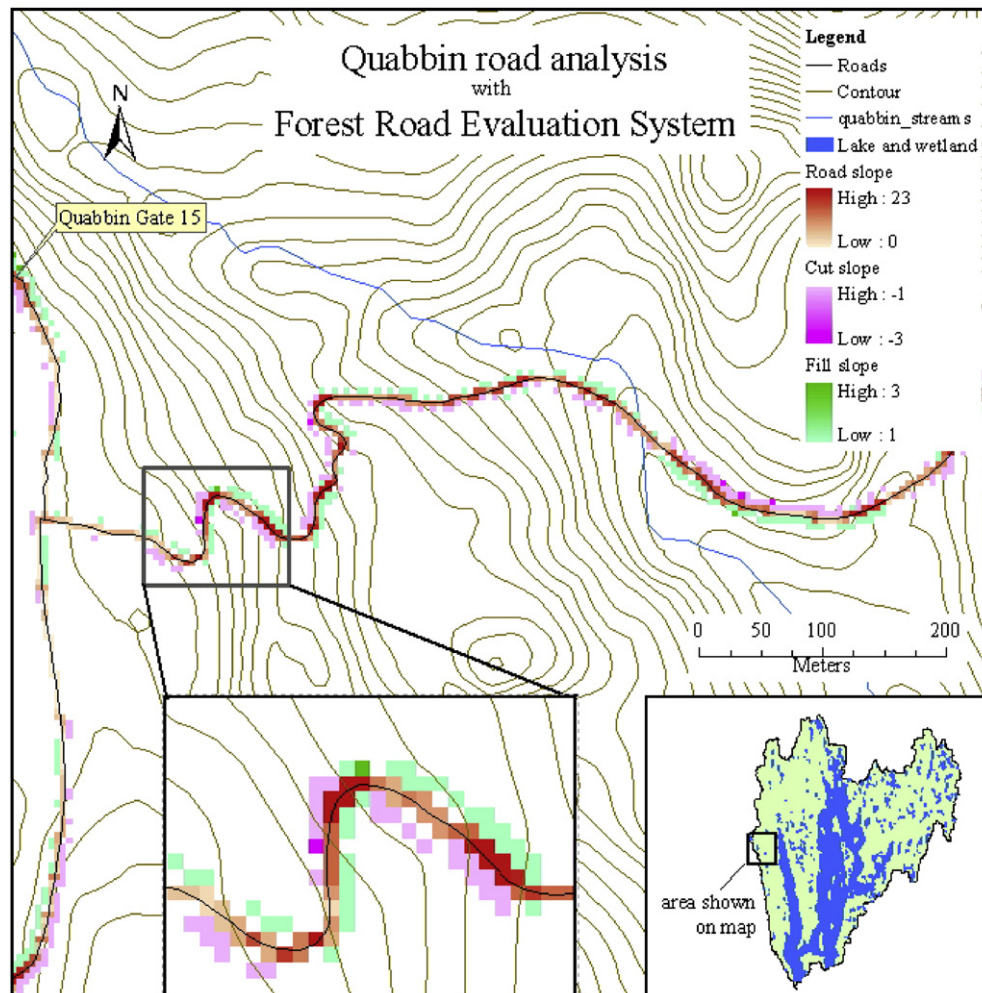


Fig. 5. Quabbin road analysis with Forest Road Evaluation System (FRES).

growth after harvest, Y_i is treatment index ($0 \leq Y_i \leq 1$) 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

Table 1

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

Total length	64,332 m
Stream 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 < slope ≤ 5%: 46,760 m (73%) 5% < slope ≤ 10%: 12,391 m (19%) 10% < slope ≤ 15%: 1766 m (3%) 15% < slope: 182 m (0.3%)

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.

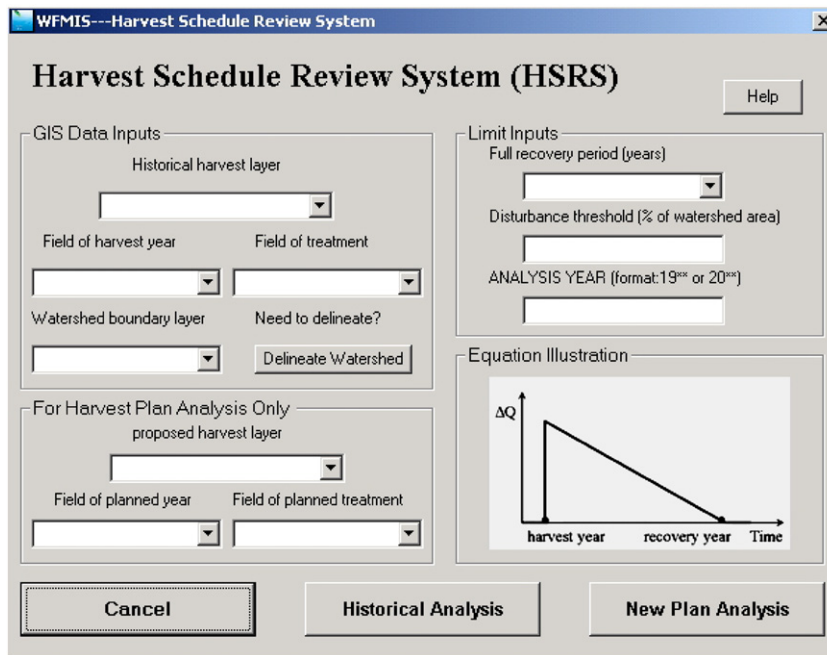


Fig. 6. Interface of Harvest Schedule Review System (HSRS).

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.

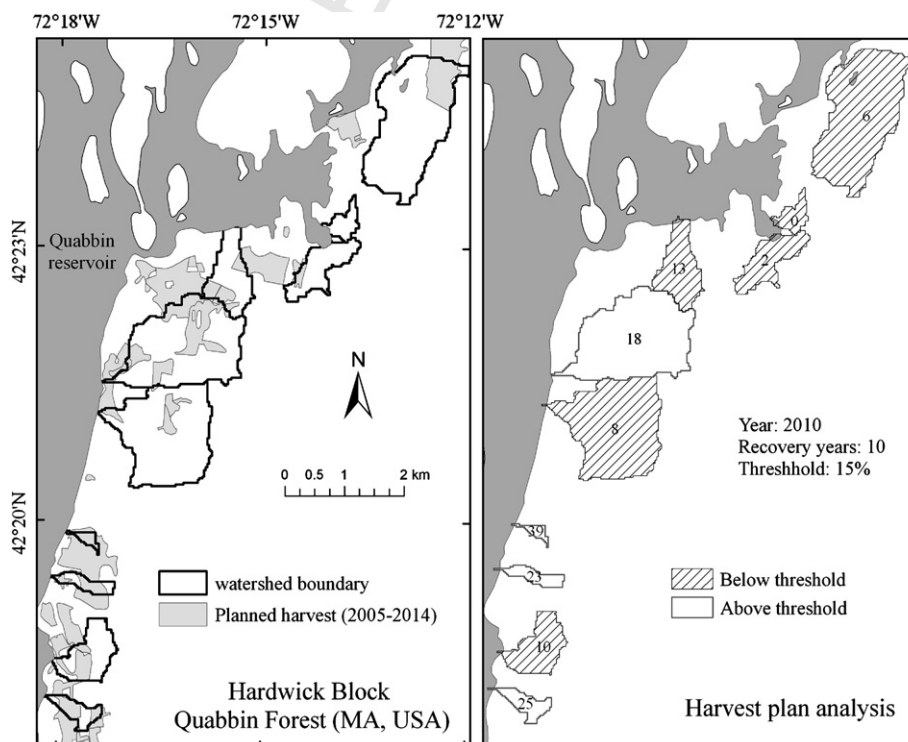


Fig. 7. Test of Harvest Schedule Review System (HSRS) with Hardwick Block (Quabbin Forest, MA) harvest data.

Uncited references

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

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References

- Barten, P.K., Ernst, C.E., 2004. Land conservation and watershed management for source protection. *Journal of the American Water Resources Association* 96 (4), 121–136.
- Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55 (2), 3–23.
- Botcher, D., Hiscock, J.G., 2001. WAMView – a GIS/land source based approach to watershed assessment model. In: *Proceedings of the Water Environment Federation (WEF) TMDL Science Issues Conference*, St. Louis, MO, March 4–7, 2001.
- de la Crétaz, A.L., Barten, P.K., 2007. Land Use Effects on Streamflow and Water Quality in the Northeastern United States. CRC Press, Taylor and Francis Group, Boca Raton, FL, 319 pp.
- Douglas, J.E., 1983. The potential for water yield augmentation from forest management in the eastern United States. *Water Resources Bulletin* 19, 351–358.
- Douglas, J.E., Swank, W.T., 1972. Streamflow Modification Through Management of Eastern Forests. USDA Forest Service, Research Paper SE-94. Southeastern Forest Experiment Station, Asheville, North Carolina, 15 pp.
- Girvetz, E., Shilling, F., 2003. Decision support for road system analysis and modification on the Tahoe National Forest. *Environmental Management* 32 (2), 218–233.
- Hornbeck, J.W., Kochenderfer, J.N., 2004. A century of lessons about water resources in northeastern forests. Chapter 2. In: Ice, G.G., Stednick, J.D. (Eds.), *A Century of Forest and Wildland Watershed Lessons*. Society of American Foresters, 287 p.
- Hornbeck, J.W., Martin, C.W., Eager, C., 1997. Summary of water yield experiments at Hubbard Brook Experimental Forest, New Hampshire. *Canadian Journal of Forest Research* 27, 2043–2052.
- Kovner, J.L., 1956. Evapotranspiration and water yield following forest cutting and natural regrowth. *Society of American Foresters Proceedings* 1956, 106–110.
- Lamy, F., Bolte, J., Santelmann, M., Smith, C., 2002. Development and evaluation of multiple-objective decision-making methods for watershed management planning. *Journal of the American Water Resources Association* 38 (2), 517–529.
- Longley, P.A., Goodchild, M.F., Maguire, D.J., Rhind, D.W., 2001. *Geographic Information Systems and Science*. Wiley, pp. 288–291.
- Lull, H.W., Reinhart, K.G., 1967. Increasing Water Yield in the Northeast by Management of Forested Watersheds. USDA Forest Service Research Paper NE-66. Northeastern Forest Experiment Station, Upper Darby, PA, 45 pp.
- Mas, J.F., Puig, H., Palacio, J.L., Sosa-López, A., 2004. Modelling deforestation using GIS and artificial neural networks. *Environmental Modelling and Software* 19 (5), 461–471.
- McCammon, B., Rector, J., Gebhardt, K., 1998. A Framework for Analyzing the Hydrologic Condition of Watersheds. BLM Technical Note 405. USDA Forest Service and USDI Bureau of Land Management, Washington, D.C., 37 pp.
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2005. *Soil Water Assessment Tool Theoretical Documentation*. Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas, 541 pp.
- NRC (National Research Council), 2000. *Watershed Management for Potable Water Supply: Assessing New York City's Approach*. National Academies Press.
- Pullar, D., Springer, D., 2000. Towards integrating GIS and catchment models. *Environmental Modelling and Software* 15 (5), 451–459.
- Rao, M., Fan, G., Thomas, J., Cherian, G., Chudiwale, V., Awawdeh, M., 2007. A web-based GIS decision support system for managing and planning USDA's conservation reserve program (CRP). *Environmental Modelling and Software* 22 (9), 1270–1280.
- Swank, W.T., Vose, J.M., Elliott, K.J., 2001. Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. *Forest Ecology and Management* 143, 163–178.
- Swank, W.T., Swift Jr., L.W., Douglass, J.E., 1988. Streamflow changes associated with forest cutting, species conversions, and natural disturbances, pp. 297–312. In: Swank, W.T., Crossley Jr., D.A. (Eds.), *Forest Hydrology and Ecology at Coweeta*. Ecological Studies, vol. 66. Springer-Verlag, New York.
- USDA Forest Service, 2000. *Forest Roads: A Synthesis of Scientific Information*. USDA Forest Service, Washington DC, 117 pp.
- US EPA, 1996. *Nonpoint Source Pollution: The Nations' Largest Water Quality Problem*. EPA841-F-96-004A. US EPA, Washington DC.
- US EPA, 2000. *Environmental Planning for Communities: A Guide to the Environmental Visioning Process Utilizing a Geographic Information System (GIS)*. EPA/625/R-98/003. US EPA, 49 pp.
- Verry, E.S., 1986. Forest harvesting and water: the Lake States experience. *Water Resources Bulletin* 22 (6), 1039–1047.
- Weintraub, L.H.Z., Chen, C.W., Herr, J., 2001. Demonstration of WARMF: a decision support tool for TMDL development. In: *Proceedings of the Water Environment Federation (WEF) TMDL Science Issues Conference*, St. Louis, MO, March 4–7, 2001.
- Wemple, B.C., Swanson, F.J., Jones, J.A., 2001. Forest roads and geomorphic process interactions, Cascade Range, Oregon. *Earth Surface Processes and Landforms* 26, 191–204.
- Zhang, Y., Barten, P.K., Sugumaran, R., DeGroot, J., 2008. Evaluating forest harvesting to reduce its hydrologic impact with a spatial decision support system. *Applied GIS* 4 (1), 1–16.
- Zhang, Y., 2006. *Development and Validation of a Watershed Forest Management Information System*. Ph.D. dissertation, University of Massachusetts Amherst, 131 pp.