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Evaluating Forest Harvesting to Reduce its Hydrologic Impact with a Spatial Decision Support System

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Evaluating forest harvesting to reduce its hydrologic impact with a spatial decision support system

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Abstract: Timber harvesting changes the condition of forest ecosystems, which are a major influence on the characteristics of headwater streams. Such characteristics include the quantity and timing of base flow and storm flow, concentrations of sediment and dissolved nutrients, water temperature, and the stability of the stream channels. This paper explores previous studies dealing with the relationship between timber harvesting and its hydrologic effects, especially long term water yield increase. The watershed disturbance threshold theory is raised and investigated in detail. The development and evaluation of a spatial decision support system, the *Harvest Schedule Review System (HSRS),* is then described. The *HSRS* will aid in the minimization of hydrological impacts of forest harvesting, along with its related, negative environmental influences. It provides a spatially and temporally explicit tool for users to analyze the hydrologic impact of forest harvest schedules.

Key words: Forest harvesting, Hydrologic effects, SDSS, GIS, Water yield

1 Introduction

The condition of forest ecosystems is a major influence on the characteristics of headwater streams. Forest change generally leads to changes in the quantity and timing of base flow and storm flow, concentrations of sediment and dissolved nutrients, water temperature, and the stability of the stream channels (Cretaz and Barten, 2007). Indeed, the relationship between forest and water is complex, and over the past several decades the public has become much more aware of land management practice effects on the natural environment. However, misconceptions about this relationship still exist (Stuart and Edwards, 2006).

For example, although people usually think that water from a forested watershed is clean, nitrate concentration from old aged stands is much higher than from medium aged stands (Leak and Wayne, 1975). Also, it is generally believed that negative consequences are normally linked with timber harvesting, but well planned and carefully conducted forest management operations usually result in only short term change to stream water chemistry that are within the natural variability in which the stream ecosystems exist and have evolved (Stuart and Edwards, 2006).

A careful operation would include a scientific plan and the adoption of best management practices (BMPs), but how to properly plan forest harvesting to avoid negative impacts is always a challenging question for foresters. Accordingly, this paper briefly summarizes historical studies on the effects of forest harvest on water yield and then raises the watershed disturbance threshold theory. This is followed by the development and evaluation of the Harvest Schedule Review System (HSRS), which is a spatial decision support system (SDSS) and which is described in detail below. The HSRS is intended to assist forest harvest planning in order to protect water resources.

2 Effects of forest harvest on water resources

In order to aid forest harvest planning, the environmental impacts of forest harvesting, especially the impact on water, need to be studied. This subject has been a research topic for more than a century (Verry, 1986). The first American watershed experiment, begun in 1909 at Wagon Wheel Gap in Colorado, was a comprehensive study to quantify the effects of deforestation on the volume and timing of stream flow, soil erosion and sediment loading. Since then, similar studies have been conducted throughout the U.S. (Megahan and Hornbeck, 2000).

Hibbert (1967) summarized the results from 39 experiments (U.S.A., Kenya, Japan, and South Africa) and came up with common generalizations including:

- reduction of forest cover increases water yield, and
- reestablishment of forest cover, on sparsely vegetated land, decreases water yield.

Also, Bosch and Hewlett (1982) reviewed 55 additional studies throughout the world (U.S.A., Canada, South Africa, New Zealand, Australia, and Japan) and they reinforced these two generalizations.

To explain them, the water balance equation should be considered. Within any watershed, water yield (Brooks et. al., 1997) is calculated as:

$$Q = P - ET \pm \Delta S \pm L \qquad (1)$$

where: Q = water yield (stream flow + groundwater recharge)
P = precipitation
ET = evapotranspiration
S = storage
L = leakage, in or out of the watershed.

Evapotranspiration (ET) includes three factors — interception, evaporation, and transpiration — all of which are related to forest cover.

Now, for a given watershed suppose that precipitation (P), storage (S), and leakage (L) do not change much from year to year under normal conditions. Timber harvesting will then generally lead to less transpiration and canopy interception (Hornbeck et al., 1997). Moreover, ET will be reduced and, in consequence, water yield (Q) and peak flow will increase.

Hence at Coyote Creek watershed (western Oregon), average water yield increased by 70% after clear cutting (Harr, 1976). Also, Kovner (1956) considered precipitation variance in

Coweeta watershed (North Carolina) and showed that the stream flow increases were independent of the annual precipitation after harvesting. Finally, 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. So we can safely conclude that after timber harvesting, water yield will increase in humid temperate forests.

Water yield increase may cause many kinds of problems, such as wetter soils, nutrient mobilization, decreased water quality, and increased channel erosion. Especially when the increased stream flow occurs as augmentation of peak flows, it can exacerbate erosion, transport of sediment and nutrients, and it can cause damage to roads and structures (Lull and Reinhart, 1967; Hornbeck et al. 1997). It is necessary, therefore, to study the relationship between timber harvesting and water yield increase, as well as the long term change of this increase.

Previous studies have produced many mathematical conclusions about the hydrological response of forest harvesting. Douglas and Swank (1972) reviewed 22 cutting experiments conducted in Coweeta, Fernow (West Virginia), Leading Ridge (Pennsylvania), and Hubbard Brook (New Hampshire) and they built a linear relationship between the first year stream flow increase after treatment and the percentage of basal area (or land area) cut. It has been found that clear cutting aspen will at least double peak stream flow rates resulting from snowmelt within lake states (Verry, 1986). Also, Lull and Reinhart (1967) concluded that clear cutting on a well stocked forested watershed in the Northeast United States increased annual water yield during the first year after treatment by about 100 to 300 mm. Five years after harvesting, the water yield change was about one third of the first year increase, but the water yield increase disappeared after approximately10 years.

In addition, Swank et al. (2001) reported that after clear cutting a 59 ha watershed, stream flow increased by 28% and it took 5 years to return to baseline stream flow and increases in sediment yield were observed downstream over the next 15 years. Similarly, Moore and Wondzell (2005) reviewed relevant studies within the Pacific Northwest area and concluded that recovery to pre-harvest conditions appeared to occur within about 10 to 20 years in some coastal catchments, but may take many decades in mountainous, snow dominated catchments. Note that some studies found that the initial water yield increase after timber harvesting will decline logarithmically back to the base yield from a well-stocked forest (Kovner, 1956; Lull and Reinhart, 1967; Douglas, 1983). Finally, Douglas (1983) derived three equations for deciduous forests based on annual insolation to calculate the initial increase, duration of the increase, and the increase in relation to the year after the harvest. All of these studies provide a good knowledge base for future study.

Bosch and Hewlett (1982) pointed out that water yield increase caused by forest harvesting could be modeled with computer simulators and thus were predictable to some degree. This is confirmed by our literature review which demonstrated the existence of the substantial knowledge base. Useful tools can be developed based on this knowledge base to enable better forest management to protect water resources.

However, most tools related with forest harvest, such as C*ASCADE* (Wallin et al., 1996), *DISPATCH* (Baker, 1999), *HARVEST* (Gustafson and Rasmussen, 2002), and *LANDIS* (Zollner et al., 2005), are pattern generation/simulation models which try to predict age distribution, forest composition, and patch structure. None of them focuses on the analysis of the relationship between forest harvest and water yield. It is necessary, therefore, to develop a new tool to evaluate harvest plans to minimize the potential negative hydrological impacts.

3 Forest disturbance threshold theory

There are many studies showing a "disturbance threshold" for the influence of forest harvesting on water yield (Zhang, 2006). This threshold may be the proportion of treated area or biomass removal in the watershed, and below this threshold, water yield will not be significantly affected. Because the magnitude of the water yield increase will depend on the proportion of the watershed area cut, the size of individual clearings, and the condition of the forest stand before cutting, thinning may have only a negligible effect on water yield, and partial cutting may have only a minor effect on water yield for uneven aged forests (Lull and Reinhart, 1967; Anderson et al. 1976).

More specifically, Bent's (1994) study at the Quabbin Reservoir (MA) showed that if the decrease in basal area approaches 25%, there would be a measurable increase in water yield. Also, an experiment conducted in New Hampshire (Hornbeck et al., 1997) found that clear cutting followed by herbicide treatment caused water yield to increase by 347 mm (41%). By contrast, strip cutting resulted in a 114 mm (8%) water yield increase. These increases diminished rapidly as the forest regenerated and were undetectable within 7 to 9 years after treatment. Finally, Hornbeck (1993, 2004) concluded that at least 25-30 percent of basal area must be cut to produce a measurable water yield increase.

There are many other studies that strengthen the threshold theory. For example, Douglas and Swank's model (1972) showed that the first year stream flow increase for the Appalachian Highlands was primarily dependent upon the reduction in basal area during harvest. It was noticed that the stream flow increase was generally greater for north facing than for south facing watersheds. This reflects the solar energy received by watersheds of different slopes, aspects, and latitudes (Swank et al., 1988).

Douglas and Swank (1975) took these factors into account in the solar energy function that was termed the "insolation index". They derived a more accurate model to predict the first year change in water yield after timber harvesting. It was found that the increased rate of water yield is much higher when the reduction in basal area is more than 20%. They also showed that converting from hardwoods to white pine greatly reduces stream flow. Also, Bosch and Hewlett's (1982) review of 94 experimental watershed studies confirms that water yield increases are not detectable if less than 20 percent of a watershed is harvested.

Although these studies corroborated the existence of the proposed disturbance threshold, it is related to local climate, topography, soil, and forest species composition and structure. Therefore, a fixed general value for this harvest disturbance threshold does not exist. Watershed managers need to establish a value according to local natural conditions.

4 Calculation of the disturbance index

The first question addressed in the design of *HSRS* was how to calculate the accumulated watershed harvesting effect. There are inherent difficulties in this task. The variables that must be simultaneously considered over large heterogeneous areas include:

1) the possibility of repeated harvests (thinnings),
2) many small harvest units in any given watershed, and
3) re-growth after each harvest.

The *HSRS* must account for all these factors, and so the disturbance index, R, was developed in an attempt to do so:

$$R = \frac{\sum(XYA)}{TotalWatershedArea} \quad (2)$$

where: R = disturbance index
X = recovery time index (from 0 to 1)
Y = treatment index (from 0 to 1)
A = area of the management unit within the study watershed

The recovery time index (X) accounts for tree growth after harvesting. For example, suppose that the forest will be fully recovered in 10 years and that the analysis year is the third year after harvesting. In the simplified linear equation, X will equal 0.7. Alternatively, if the calculation year is the 11th year after the harvest, X will be 0, since the forest's hydrologic function is fully recovered.

The treatment index (Y) represents the harvest type, that is, whether it is clear cutting, strip cutting, or thinning. It is the percentage of the harvest area in the watershed (it can also be the percentage of biomass removal) that is cut. For example, in a strip cut of a unit that is wholly located within the watershed, if the harvested area is 70% of the total area, then Y equals 0.7. By contrast, a light thinning might have a treatment index of 0.1. Table 1 shows the suggested treatment index for different regeneration methods (Gregory, 2007).

Even-aged methods	**Treatment Index**
Clear cut	1
Seed-tree	0.8-0.95
Shelterwood/Thinning border	0.5-0.6
Two-aged methods	
Clearcut with reserves	0.8-0.95
Seed-tree with reserves	0.8-0.95
Shelterwood with reserves	0.5-0.6
Uneven-aged methods	
Group selection	0.3-0.4
Patch selection(0.25-0.50 acre)	0.5

Table 1 - Treatment Index suggestions

Note that there could be many harvest units that are wholly or partially located in the watershed. They also might be cut in different years. The calculation must, therefore, track all of these units and their X, Y, and A values, then sum them up to find the accumulated effects of cutting and re-growth. This composite value is then divided by the area of the watershed to get the disturbance index (R).

Figure 1 is an illustration of the calculation of disturbance index with a harvest scenario for one watershed. There are four management units crossing the watershed boundary. Units 1 and 2 have been harvested 3 years (50% cut) and 5 years (30% cut) ago respectively. The Full recovery period is 10 years. This year's harvest plan is clear cutting of unit 3. Areas shown in the map are the areas of the management unit within the watershed. Based on equation 2, if the plan is processed, the disturbance index for the whole watershed would be 39.0%. This number can be compared with the watershed's disturbance threshold.

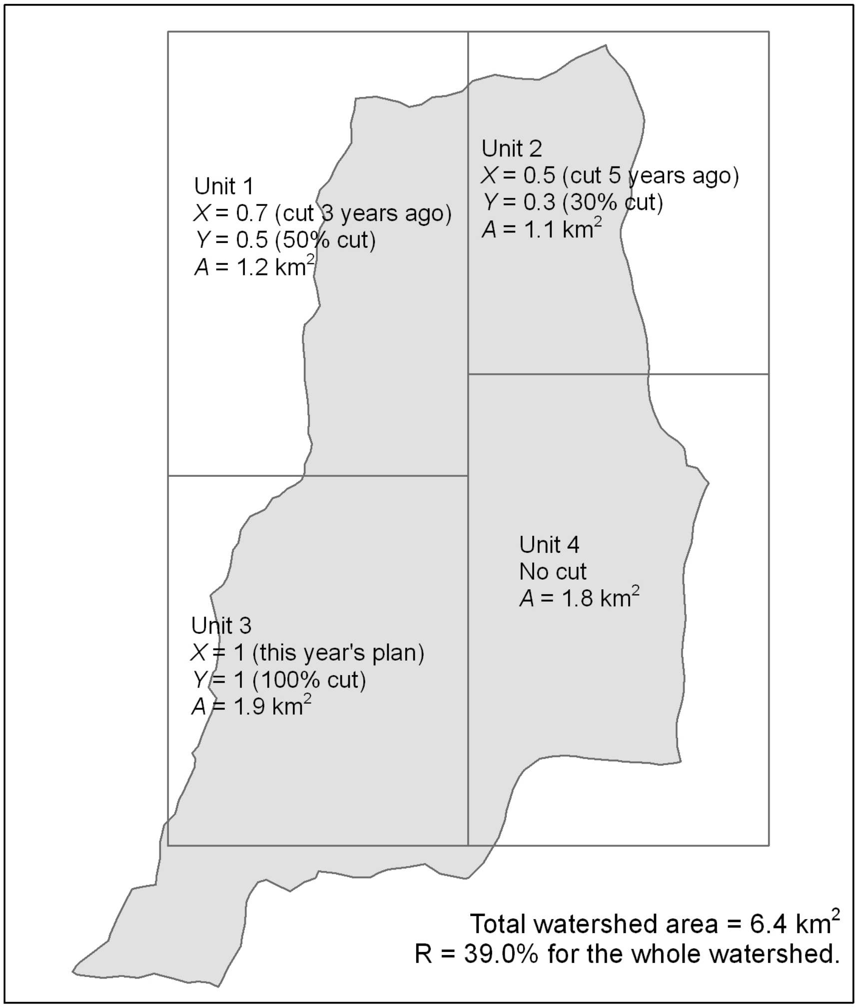

Figure 1 - Illustration of the calculation of disturbance threshold for one forest harvesting scenario

5 *HSRS* interface design

To facilitate the use of the disturbance threshold theory, the *HSRS* was developed with *ArcObjects*© and *Visual Basic*© as an *ArcGIS*© extension with user friendly interfaces. Functions in the *HSRS* include historical (retrospective) analysis and new (prospective) harvest plan analysis. The retrospective analysis uses historical harvesting data to calculate the disturbance index (R) for each watershed (block) for past and current years. This can help foresters to accurately quantify the effects of earlier cutting. Foresters can also combine this result with past water quality/quantity records to establish the local disturbance threshold. The harvest plan analysis is based on historical harvesting data (to establish initial conditions) and harvest plan data to calculate the potential disturbance index (R) for each watershed (block). This can help foresters to predict the potential effect of the harvest plan on water quantity, and make harvest plan changes as needed to protect water yield. Table 2 is a detailed explanation of the *HSRS* inputs and parameters.

Input/parameter	**Format**	**Description**
Historical harvest layer	Polygon shapefile	Including all cutting patches for each year.
Harvest year	4 digits, e.g. 1999	The name of the attribute field reflecting harvest year in the historical harvest layer.
Treatment	$0 \le Y \le 1$	No cut is 0 and clearcut is 1
Watershed boundary	Polygon shapefile	Contributing areas, the delineate watershed button links to another interface to delineate watershed based on pour points.
Proposed harvest layer	Polygon shapefile	Including all cutting patches for each year in harvest plan
Planned year	4 digits	The name of the attribute field reflecting harvest year in the proposed harvest layer.
Planned treatment	$0 \le Y \le 1$	No cut is 0 and clearcut is 1
Full recovery period	Integer	The number of growing seasons needed for the forest to return to preharvest condition
Disturbance threshold	2 digits integer, e. g. 25	The area/biomass removing threshold. If the percentage of accumulated area/biomass harvest to total watershed area/biomass is above it, water yield will be significantly changed. The value should be based on local condition (i.e. climate, tree species, topography, soil, etc).
Analysis year	4 digits	The year for which the user wants to know the accumulated harvest effect.

Table 2 - Inputs and parameters controlled by the user in HSRS

The main *HSRS* user interface for specifying the parameters is shown in Figure 2. Users can select input layers and type in parameters. The figure at the right side of the interface reflects the linear equation used in the model, which represents the long term change of water yield increase after harvesting. A linear equation can simplify the problem and it is also more conservative in relation to the purpose of this tool.

The Historical Analysis button is used to analyze historical harvest data in the historical harvest layer, and the analysis year must be within the historical record. The New Plan Analysis button allows analysis of historical harvesting data and proposed harvesting data taken together. For example, suppose the historical data covers the period from 1960 to 2005, the harvest plan data covers the period from 2006 to 2015, the full recovery period is 10 years and the analysis year is 2008. In this case the *HSRS* will use historical data from 1999 to 2005 and plan data from 2006 to 2008. If the analysis year is 2015, the program will only use plan data from 2006 to 2015, because old treatment areas have fully recovered.

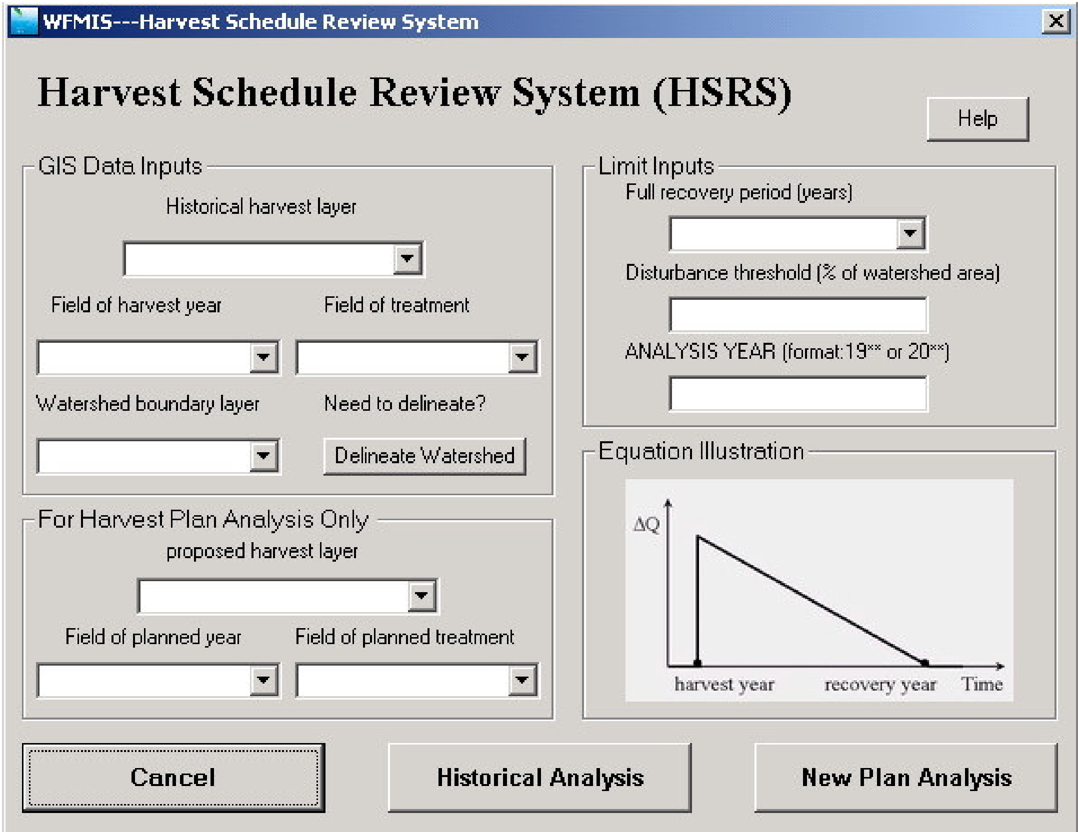

Figure 2 - Interface of the *Harvest Schedule Review System (HSRS)* (Zhang, 2006)

Figure 3 represents the analysis process for one watershed boundary. Each harvesting unit/block is checked to see whether it is within the boundary, within the analysis period and is the last management unit. If the first two answers are yes, then the unit's disturbance index will be calculated and stored. After all the units are checked and stored, individual disturbance indices are added up to see whether the total disturbance is higher than the user-set threshold, and a judgment is then given for that watershed.

The program automatically summarizes historical/planned harvest data, such as the number of years in the record, starting year and ending year, and the analysis results are saved as a new polygon shapefile. If a watershed's disturbance index is above the threshold, it is symbolized with red color, otherwise, it is green. In other words, for harvest plan analysis, red means that foresters should make changes in scheduling, location, and/or silvicultural methods to let the disturbance index stay below the hydrologic change threshold.

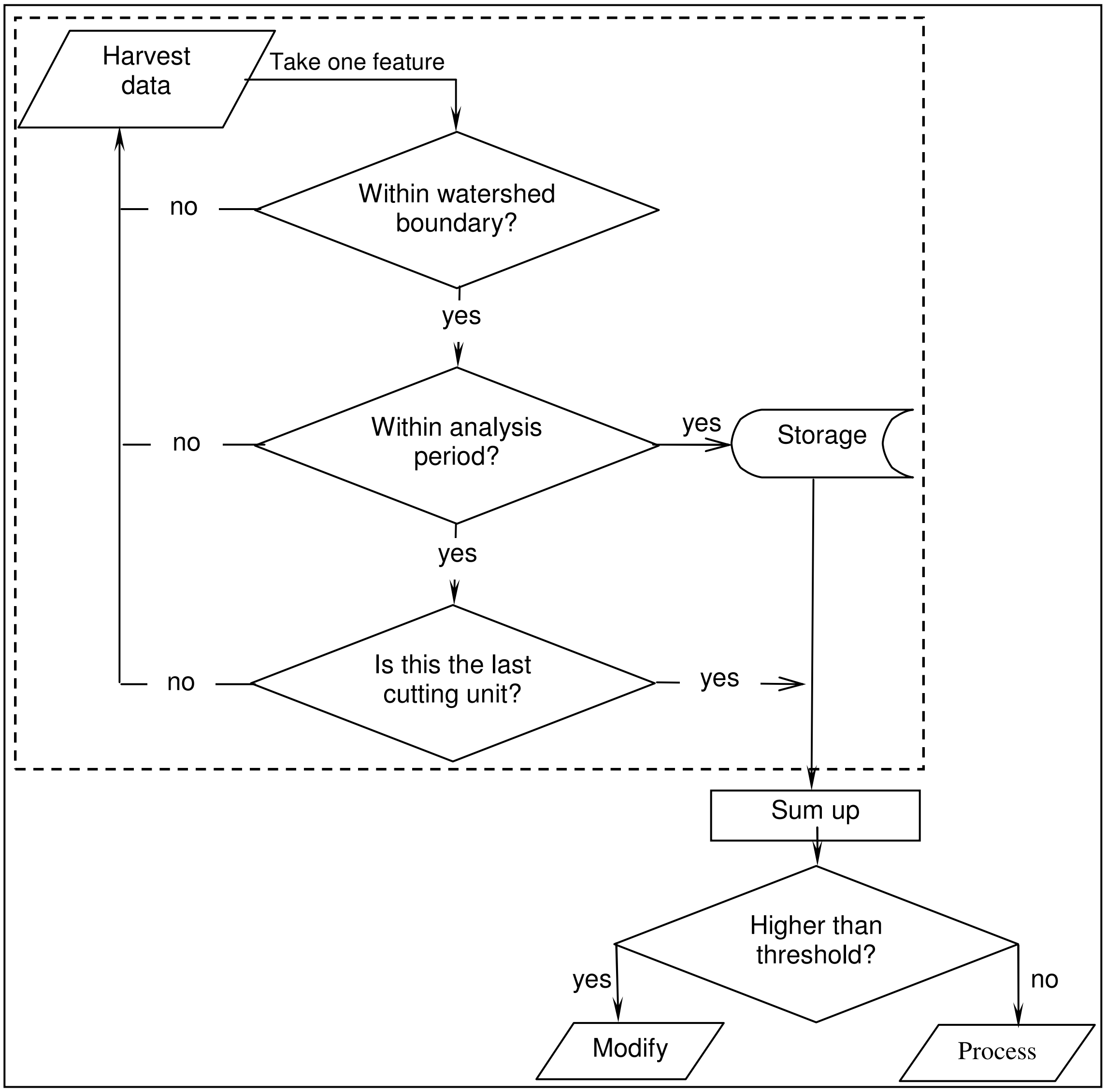

Figure 3 – Flowchart for the *Harvest Schedule Review System (HSRS*)

6 Evaluation of the *HSRS*

Quabbin watershed (Figure 4) is located in the central part of Massachusetts (U.S.A) and it serves as the primary drinking water resource for the greater Boston area with its 1.56 billion m^3 capacity. It has an area of 187 km^2 and 87% of its land, excluding the reservoir, is forest (DCR, 2007). Quabbin watershed foresters have an active management strategy to create and maintain diverse forest composition in order to provide long term drinking water protection (DCR, 2007).

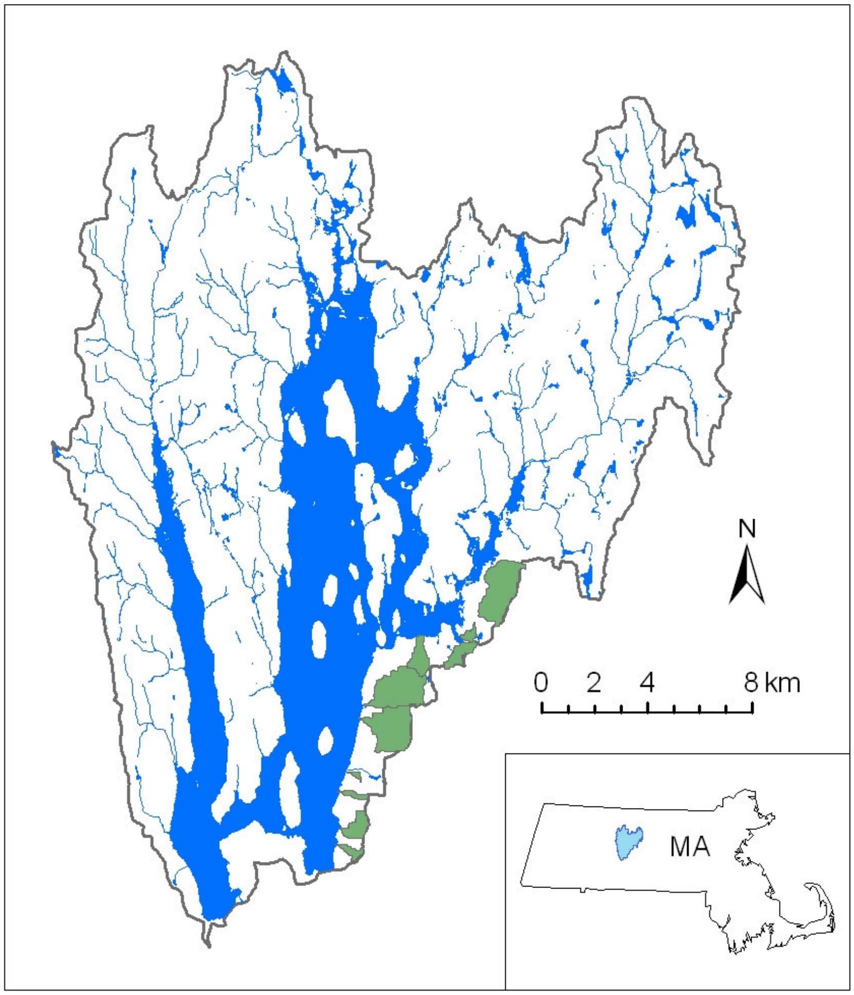

Figure 4 - The Quabbin Watershed in Massachusetts, U.S.A. The sub-watersheds (Hardwick block area) that were used to evaluate the *HSRS* are shown in green.

Currently the Quabbin watershed forest harvesting plan does not specifically consider harvesting-related changes in water yield. However their historical harvest record could be used to evaluate *HSRS* by using it for future planning. Digitized harvesting data for the Hardwick block (Figure 4), from 1963 to 2004 (43 calendar years) were obtained to give 39 years of harvesting records. The original data were modified by adding an attribute field, that is, the required treatment index. Because no definitive treatment data were available, all of the values in this field were set to 0.6 (the treatment index). For the watershed boundaries input, nine sub-watersheds, delineated at points where streams enter the reservoir, were used, as shown in Figure 5. The water quality at these points reflects upland conditions.

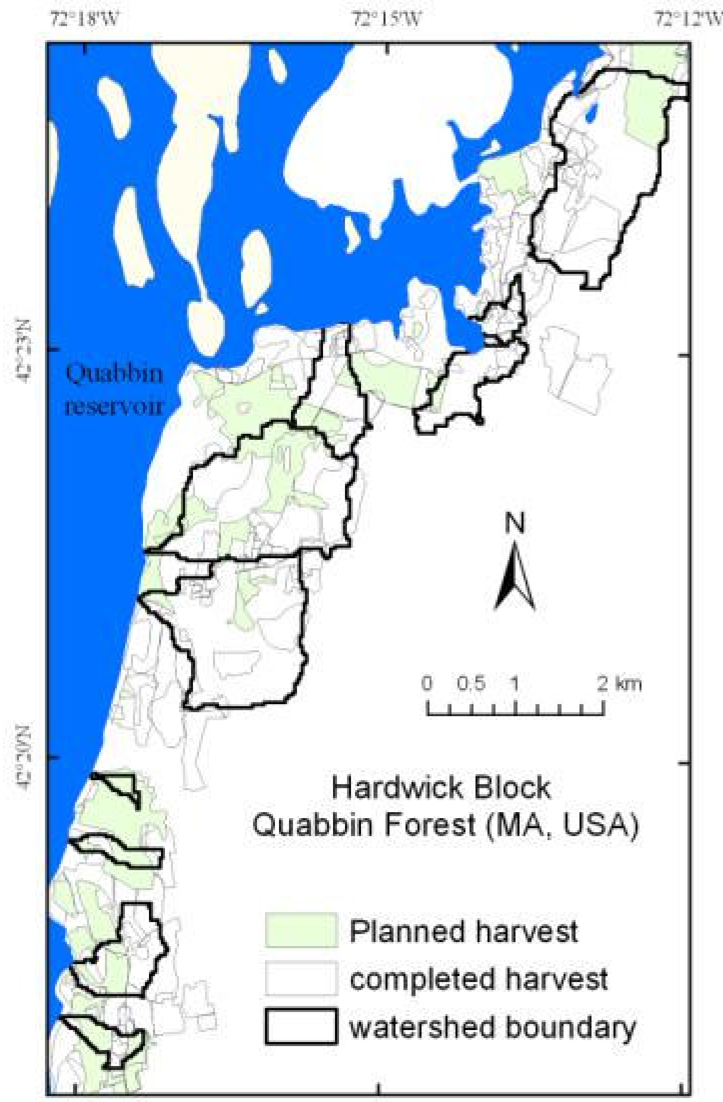

Figure 5 – The watershed boundaries used for testing the *Harvest Schedule Review System (HSRS)* using harvesting data in the Hardwick Block of the Quabbin Forest, MA, USA.

For the retrospective analysis the disturbance threshold was set at 15%, the recovery year at 10 and the analysis year at 2004, and the left panel of Figure 6 shows the *HSRS* analysis results. Each watershed is labeled with the disturbance index percentage. For example, if the label is 18, then the disturbance index was 18% after the 2004 harvest. This result clearly shows that some watersheds have a high disturbance index which means water yields from these watersheds were severely influenced by forest harvest that occurred between the years 1995 and 2004. Retrospective analysis enables managers to find historical harvesting problems. It can also be combined with historical water quality/quantity data to establish the local disturbance threshold.

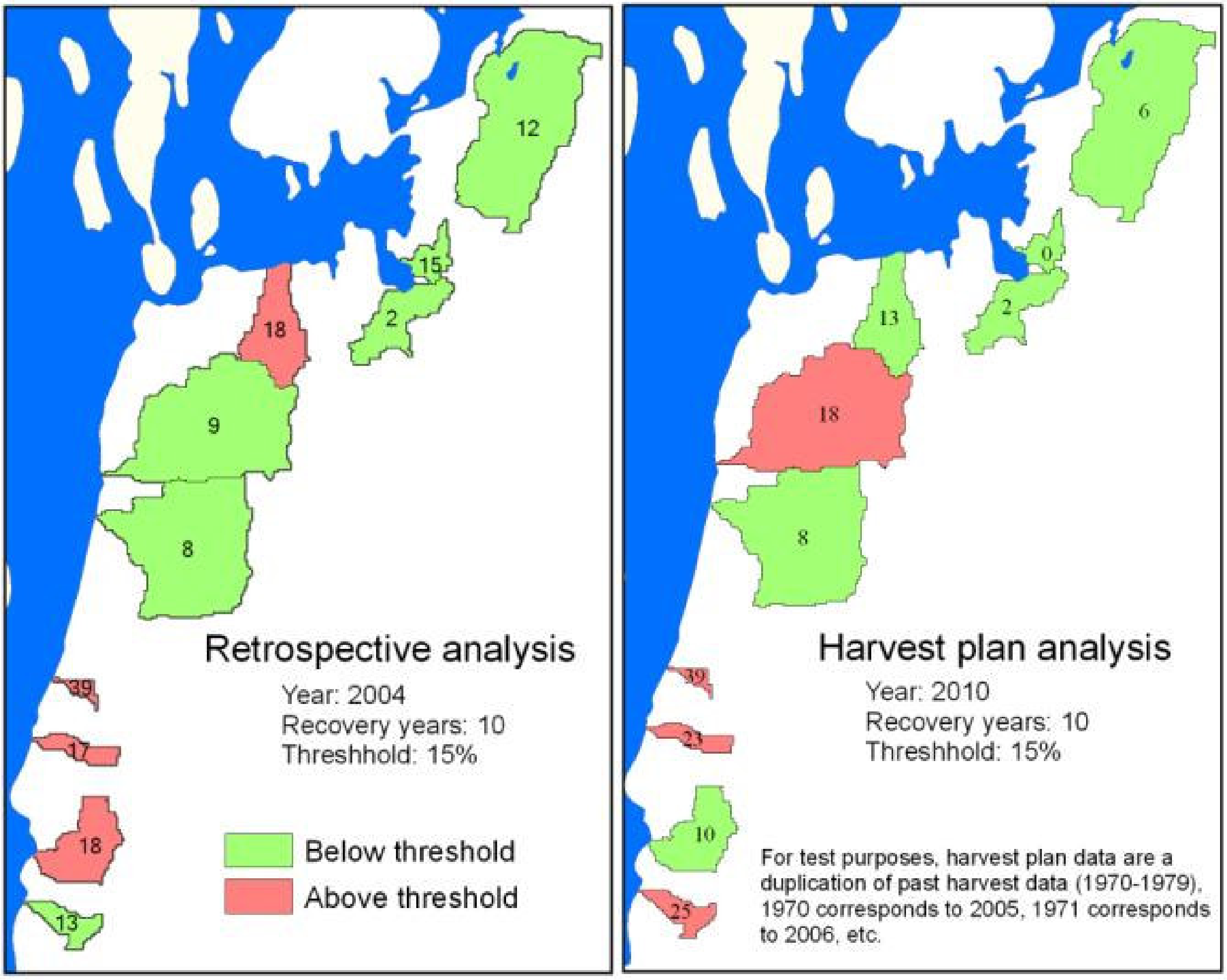

Figure 6 - Evaluation of the *Harvest Schedule Review System (HSRS)* using harvesting data in the Hardwick Block of the Quabbin Forest, MA, USA. Each watershed is labeled with the disturbance index percentage.

For the harvest plan analysis, same input parameters were used (the disturbance threshold at 15%, the recovery year at 10) and the analysis year was set as 2010. However, since harvest plan data were not available, past harvesting data (1970-1979, randomly selected) were transferred and used to represent the harvesting plan data for 2005 to 2014 (1970 for 2005, 1971 for 2006, etc.). The right panel of Figure 6 displays the result of this forecast. There are several watersheds with a disturbance index that is above the threshold, and they are highlighted to prompt users to change the harvesting plan. Possible changes can be delaying a proposed harvest by 2 or 3 years, which could allow adequate time for regeneration on earlier harvest units to ensure the watershed stays below the disturbance threshold. Another option would be to change the silvicultural method, such as reducing the percent strip cut. Similarly, shifting the harvest unit to an adjacent subwatershed or altering harvesting unit boundaries may be all that is required to avoid changes in streamflow. With its user friendly interface, the *HSRS* can achieve the goal of assisting managers to plan forest harvest to protect water resources.

7 Discussion and conclusion

It is necessary to emphasize that users of the *HSRS* need to set the disturbance threshold and recovery time based on the local situation (climate, tree species, topography, soil, etc). Also, an historical paired watersheds experiment could be used as value setting references. If an irrefutable disturbance threshold is required, a local paired watershed experiment (with several typical treatments) should be conducted on the watershed forest. But since this is a costly, difficult and long term proposition (10 or more years) it is more sensible to use published data and set the threshold and recovery times to very conservative values such as 15% and 10 years. Another choice could be using a range of values for different watersheds within the managed forest and monitoring water yield after forest harvesting. After several years of practical harvesting, managers could then find a local disturbance threshold for future planning. However, under no circumstances should users manipulate the input disturbance threshold in order to pass the harvest plan.

The disturbance index calculated by the *HSRS* is specific for the analysis watershed being considered and it only predicts water yield change at the outlet of that watershed. Within the watershed, there may be areas that have been heavily impacted by forest harvesting and thus water yields from these areas may have increased noticeably, even though these increases are not significant enough to change the total water yield of the whole watershed. For a larger watershed containing the analysis watershed, the disturbance index would be different.

Most experimental paired watersheds have an area smaller than 10 km^2, and the *HSRS* is based on these studies, so the *HSRS* is intended for managing forested watersheds of a similar scale. For larger forested watersheds, under modern forest management, water yield increases from clear cut areas will be greatly overshadowed by water flowing from uncut areas. Verry (1986) concluded that under present day land use restrictions, it is unlikely that annual streamflow from large watersheds could be changed by more than 5 percent by forest harvesting.

Also note that the *HSRS* should not be used as a harvesting reference tool for watersheds that have a large portion of agricultural or developed land cover/use because their hydrological cycles are not in a natural condition. In some areas, forest harvesting decreases annual water yield and so the *HSRS* is not applicable. For example, Harr (1982) found that in Oregon's foggy coastal range, conifer needles intercept large amounts of fog and cloud water. Hence after forest harvesting, water input and water yield are reduced at the same time.

Increasing water yield may be the purpose of some forest managers under certain conditions. To achieve this goal an increase in the disturbance index, that is, increased harvest intensity or the harvest of more trees, would be one option. A long term option could be forest composition change, such as from coniferous forest to deciduous forest.

Hydrological simulation functions could be added in the future development of the *HSRS*. This would help foresters to more precisely predict water yield change after forest harvesting. Accordingly, a user adjustable equation, reflecting the long term water yield change instead of the current linear equation, will be considered for the next version of the *HSRS*.

In summary, the *HSRS* provides a unique set of functionality for both retrospective analysis and future scenario investigation of forest management operations, along with their potential impact on water quantity at the watershed level. This spatially explicit system allows forest managers to more effectively manage the landscape in order to protect water quality which will provide environmental and economic benefits through improved control of flooding, less sedimentation, and improved aquatic habitats. Users can systematically vary the area/biomass threshold and the recovery time to evaluate past, present, and proposed harvesting plans. The *HSRS* analyzes the temporal and spatial distribution, or area and juxtaposition intersected with watershed area[s] and it uses the silvicultural method (% basal area or biomass removal) of harvesting units. All of the functions of the *HSRS* have been evaluated, and the output maps show the disturbance index for each test watershed. As noted earlier, the watersheds with a disturbance index above the user specified threshold are highlighted, prompting planners and foresters to make changes to the harvesting plan.

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