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MODELING WATER YIELD RESPONSE TO FOREST COVER CHANGES IN NORTHERN MINNESOTA

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ABSTRACT

A water yield model (TIMWAT) has been developed to predict changes in water yield following changes in forest cover in northern Minnesota. Two versions of the model exist; one predicts changes in water yield as a function of gross precipitation and time after clearcutting. The second version predicts changes in water yield due to changes in above-ground biomass production and can therefore, be linked with timber growth simulation models. Forest cover changes which can be examined include clearcutting aspen and red pine, conversion from aspen to red pine, and conversion from aspen or red pine to agricultural crops such as sugar beets, small grains and alfalfa. TIMWAT is one component of a projected package of models that will be capable of making multiple resource projections associated with land use changes.

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RESUME

On a élaboré un modèle de rendement en eau (TIMWAT) pour prédire les variations du rendement en eau consécutives à des modifications du couvert forestier dans le nord du Minnesota. Il existe deux versions du modèle. L'une prédit les variations du rendement en eau en fonction des précipitations brutes et du temps écoulé depuis la coupe à blanc. L'autre prédit les variations du rendement en eau consécutives aux changements dans la production de biomasse au-dessus du sol, et peut donc être mise en corrélation avec les modèles de simulation de la croissance des arbres. Le modèle permet l'étude des modifications suivantes de la couverture forestière: coupe à blanc du peuplier faux-tremble et du pin rouge, conversion du peuplier faux-tremble au pin rouge et conversion du peuplier ou du pin à des cultures comme la betterave à sucre, les grains ou la luzerne. TIMWAT est un composant d'un ensemble projeté de modèles qui serait capable de projeter les variations de nombreuses ressources en fonction des changements dans l'utilisation des terres.

INTRODUCTION

The forest industry in Minnesota needs wood fiber, but at the same time, there is a public desire for other products and amenities from forested lands including recreational opportunities, wildlife habitat and a stable water supply. Land managers are searching for improved ways to evaluate and then select management practices that will meet these increasing demands. In response to these needs, efforts are underway to develop computer simulation models for land managers to use in predicting, displaying and evaluating trade offs among resource components obtained from management alternatives.

To be useful, a multiple resource computer modeling framework must fit into the decision making process by using available data that will give predictions at several levels of area and time resolution used in planning. Such models should be oriented toward users and, therefore should not be too complex or expensive to operate. In such a framework, individual resource models must be compatible and have interfaces where an output from one model can be used as input for another.

A prototype multiple resource modeling framework is being developed for application in the Lake States. This paper discusses an initial stage of this effort, specifically by describing linkages between aspen and red pine forest growth models and a water yield model called TIMWAT. This linkage of models is also capable of estimating the impact of converting aspen or red pine forests to agricultural crops on resulting water yield.

FORMULATION OF TIMWAT

Studies in the Lake States indicate that water yield can be affected by changes in forest overstory conditions. For example, Verry (1972) reported a 31 percent increase in water yield following the first year of cutting aspen (Populus tremuloides Michx.) in north central Minnesota. Urie (1971) reported increases in ground water yield following thinning of Jack pine (Pinus banksiana Lamb.) and red pine (Pinus resinosa Ait.) in Michigan.

When comparing ground water yields in Michigan, Urie (1967, 1977) found that pines used more water than hardwoods. These findings were affirmed by Sartz and Harris (1972) and Sartz (1976) in Wisconsin. Ten years after plantation establishment of red pine, eastern white pine (Pinus strobus L.) and European larch (Larix decidua Mill.), the pine and larch plantings were using more water than nearby natural hardwood forests and adjacent grass and forb cover. Sartz (1963) reported similar findings from a lysimeter study in which pine plantings had higher evapotranspiration rates than hardwoods and annual grains. Therefore, water yield decreases when pines are planted on former hardwood and grass sites, and water yield increases when forest cover is converted to small grains.

Verry (1976) proposed using interception differences between mature red pine stands and aspen stands to provide a conservative estimate of water yield changes resulting from the conversion of aspen to red pine. After calculating the relationships between gross and net precipitation for aspen and red pine, the changes in net precipitation due to conversion were predicted.

In a study of the effects of clearcutting and regeneration of aspen on water yield, Paul and Verry (1980) analyzed precipitation and water yield for six years after aspen removal. The initial increase in water yield diminished with the regrowth of aspen. The following relationship was developed to predict changing water yield as the aspen regenerated:

$$\Delta Q = 43.20 + 0.09(Pg) - 41.91(\log_e T)$$

where

ΔQ = predicted change in annual water yield above mature forest conditions (mm),

Pg = gross average annual precipitation (mm),

T = time since clearcutting (years)

An alternative to the above equation is to substitute time since cutting with a timber stand characteristic, such as biomass, in units of weight per unit area. Biomass represents the accumulated growth of vegetation at a given point in time and, therefore, is an indicator of interception storage (leaf area), the extent of rooting and overall consumptive use. Although not directly measured in forest inventories, biomass can often be estimated from inventory data using prediction equations, such as those presented by Bella and Franceschi (1980). Relationships among aspen stand characteristics and water yield following a clearcut and regrowth sequence were developed from information obtained on an aspen clearcutting treatment imposed at the Marcell Experimental Forest near Grand Rapids, Minnesota, using 10 years of post-cutting data (Figure 1). The relationship illustrated in Figure 1 applies over a range of precipitation from 425 to 1000 mm and a range of biomass from 2 to 25 tonnes per hectare.

Based upon previous studies by Swank and Douglas (1974), and Verry (1976), a relationship was developed to assess changes in water yield due to conversion from aspen to red pine. To estimate the change in water yield, a hypothetical red pine stand with a site index of 18 meters and an initial density of 988 stems per hectare was established. Thinning was assumed to begin at age 40 and repeated every 10 years. This stand provided the basis for the following assumptions. First, a constant reduction of 84 millimeters of annual water yield would result from interception differences between aspen at 23 square meters per hectare basal area (BA) and red pine at 32.1 BA over a range of annual precipitation; this assumes that water yield changes are due only to interception differences between red pine and aspen (Verry, 1976). Since transpiration by hardwoods during leafless periods is less than in pines (Swank et al. 1972), this relationship would likely underestimate the actual differences in water yield. Second, it takes approximately 10 to 15 years for crown closure to occur in a red pine stand (Lundgren, 1981). After closure, water consumption in the pine stand will be equal to or greater than that of the original aspen stand. Such an occurrence was reported for an eastern white pine stand in South Carolina (Swank and Douglass, 1974). Third, at 40 years, leaf area will have reached a stable value and the majority of growth will be taking place in the bole (Laidly, P. R., pers. comm., 1981); the live crown does not lengthen significantly after this maturity is reached. Therefore, leaf area and, consequently, interception will no longer increase with age of

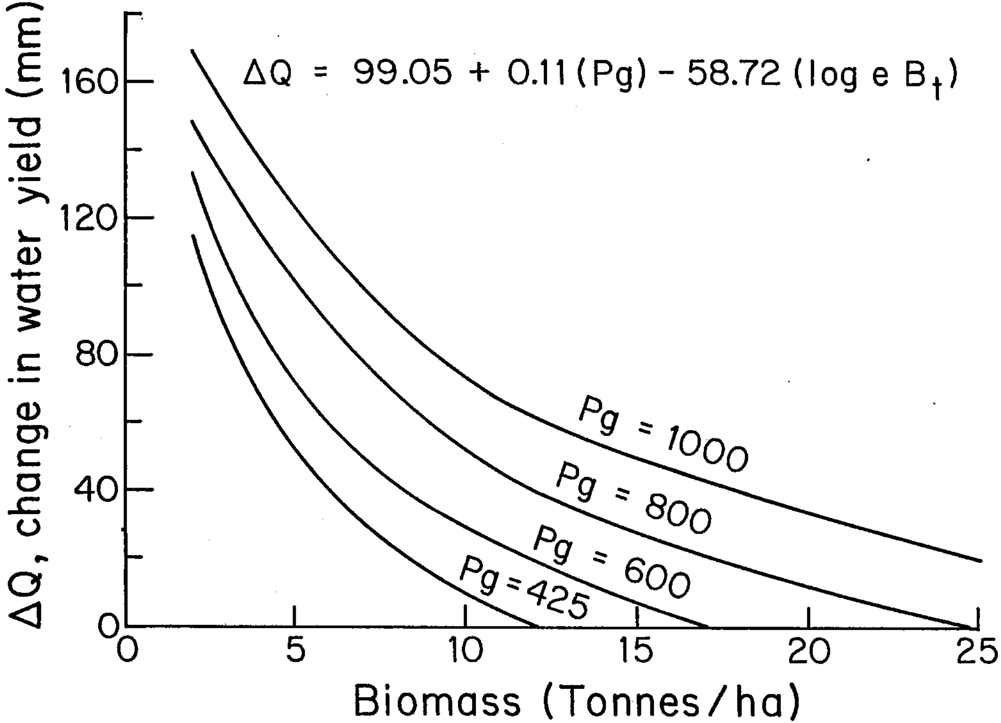

Figure 1. Biomass relationship for Watershed 4, Marcell Experimental Forest, following clearcutting of aspen.

the stand. Equations by Alban and Laidly (1981) were used to convert timber inventory data into above-ground biomass for the forest conversion relationship in Figure 2. By using the same above assumptions and adding the difference in interception between aspen and red pine (84 mm) to the resulting first year increase, the change in water yield due to clearcutting the red pine stand can be estimated (Figure 3).

A fourth land use activity which can be evaluated with the model is the conversion of forest stands to agricultural crops. Paul and Verry (1980) illustrated changes in water yield due to conversion of aspen to crops by using consumptive use data for small grains and sugar beets (Baker, 1973; Soine and Severson, 1975; Severson and Wallingford, 1976). On an annual basis, less water is consumed by small grains and sugar beets than forests; this allows a portion of the increase in water yield from cutting a forest to remain available for runoff. Conversely, alfalfa is a perennial crop which has a rooting depth similar to that of aspen when it matures. The initial increase in water yield will decrease to normal after 3 to 4 years of growth. However, alfalfa is typically not left in the same field for more than 5 to 6 years. Therefore, an average annual value was used to estimate consumptive use of alfalfa. Because the source data were obtained using crop rotation and because we wanted to develop general relationships, a mean value of consumptive use for all crops was used to estimate the change in water yield due to conversion from aspen or red pine stands to crops.

Regression coefficients were developed for each of the aforementioned relationships and incorporated into two versions of TIMWAT. One version of TIMWAT can be used to estimate water yield changes as a function of time after timber cutting (Table 1). This is a "stand alone" version which does not require biomass data. The second version of TIMWAT requires biomass data and therefore can be linked to a timber growth simulation model that provides such information (Table 2). Because some of the relationships are based on assumptions and hypothetical data, gross precipitation was not included as an independent variable, but was set at a mean Lake State value of 750 mm.

TIMWAT is capable of estimating water yield change for a single clearcut unit, a clearcut unit within a larger planning unit or watershed, or several land use changes within a large unit. Effects of land use change which occur once or consecutively for many years can be simulated by weighting ΔQ's with appropriate areas of land use change. The coefficients discussed in this paper are the values used in the program, however, users can identify their own coefficients in adapting to other regions or in identifying alternative land use changes.

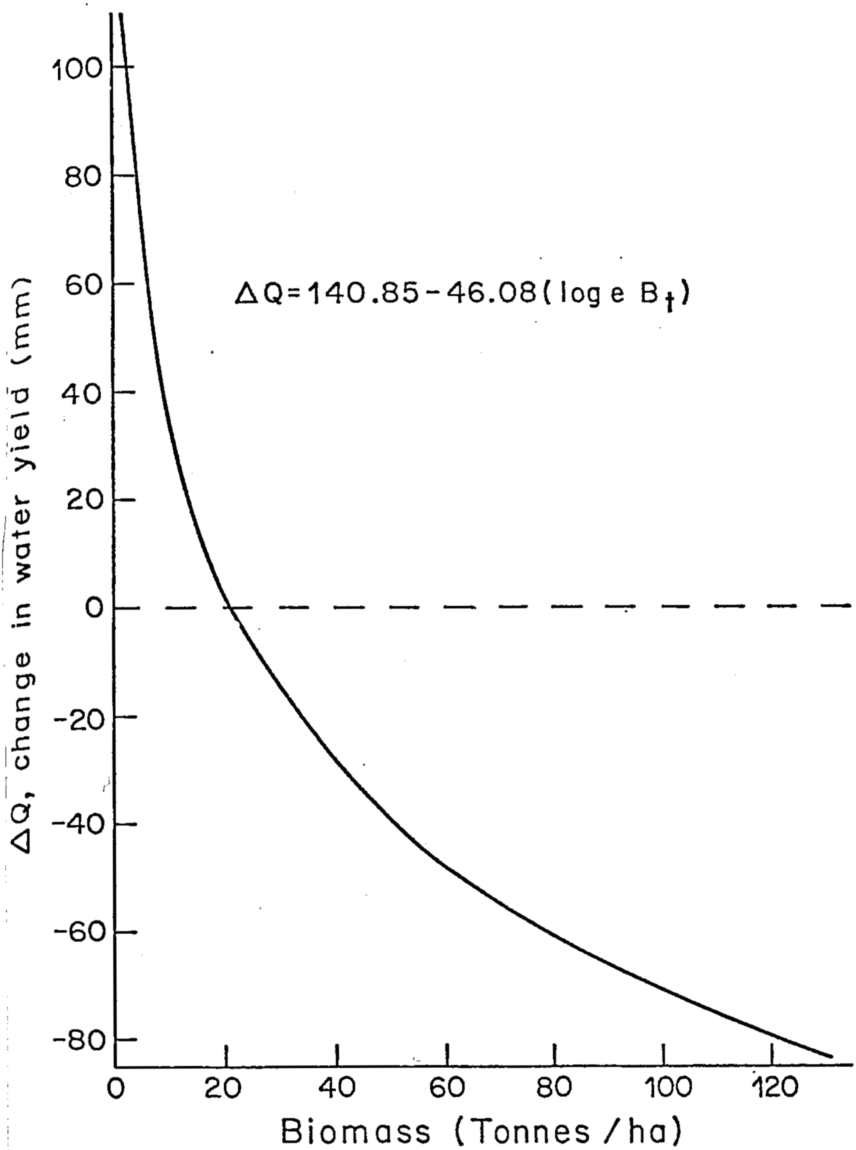

Figure 2. Relationship between change in water yield and biomass of red pine after conversion from aspen for an average annual precipitation of 750 mm.

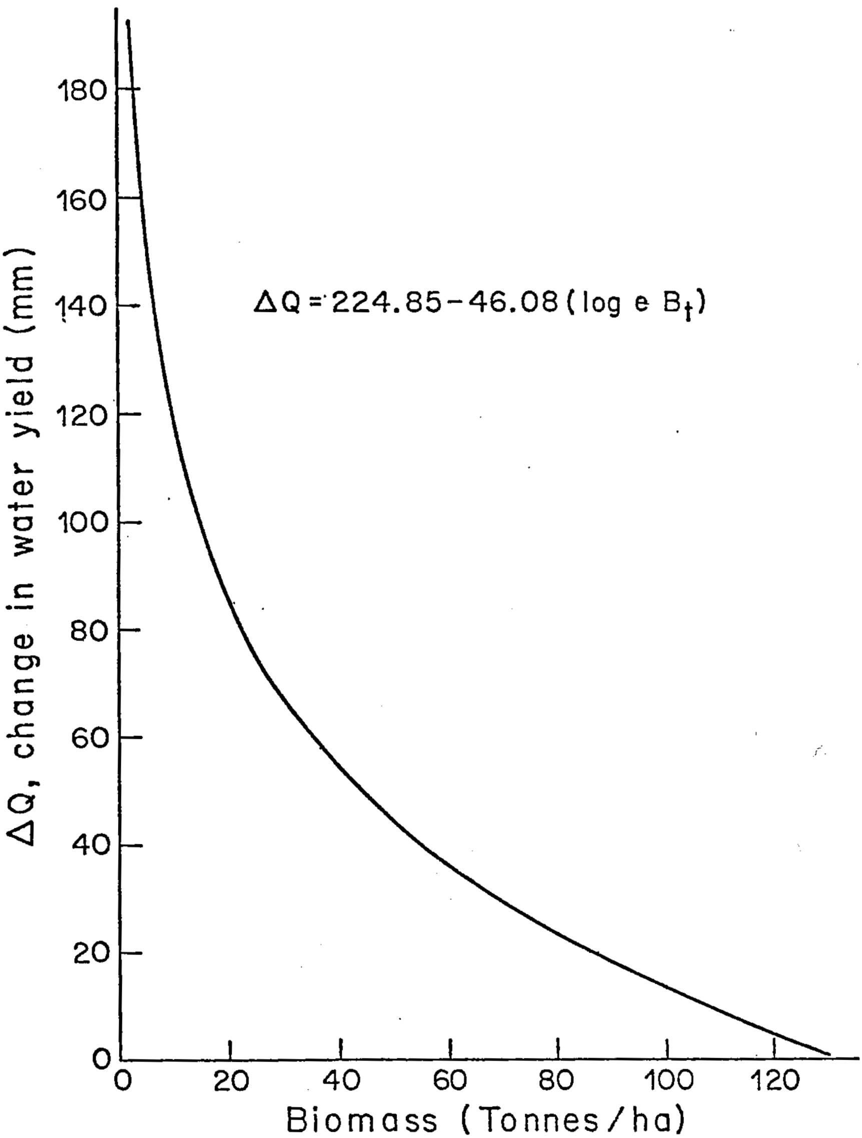

Figure 3. Relationship between change in water yield and biomass after clear-cutting and replanting a red pine stand for an average annual precipitation of 750 mm.

Table 1. Land management options and respective coefficients for the "stand alone" version of TIMWAT.

Option[a]	Coefficient for Regression Equation $\Delta Q = a + b(Pg) - c(\log_e T)$ a	b	c
1	43.20	0.09	41.91
2[b]	116.84	0	54.36
3[b]	200.66	0	54.36
4	75.18	0	0
5	159.00	0	0

[a] Options:

1 clearcutting aspen with aspen regeneration
2 clearcutting aspen, conversion to red pine
3 clearcutting red pine, red pine regeneration
4 clearcutting aspen with conversion to crops
5 clearcutting red pine with conversion to crops.

[b] Hand fit equations for average annual precipitation of 750 mm.

Table 2. Land management options and respective coefficients for the version of TIMWAT based on biomass (B_t).

Option[a]	Coefficient for Regression Equation $\Delta Q = a + b(Pg) - c(\log_e B_t)$ a	b	c
1	99.05	0.11	58.72
2[b]	140.85	0	46.08
3[b]	224.85	0	46.08

[a] Options:

1 clearcutting aspen with aspen regeneration (B_t from 2 to 25 tonnes/ha)
2 clearcutting aspen, conversion to red pine (B_t from 2 to 131 tonnes/ha)
3 clearcutting red pine, red pine regeneration (B_t from 2 to 131 tonnes/ha)

[b] Hand fit equations for average annual rainfall of 750 mm.

APPLICATION

TIMWAT was developed to facilitate analysis such as those performed by Paul and Verry (1980). To illustrate the use of TIMWAT, the Timber Management Plan of the Chippewa National Forest (U.S.F.S. 1975) will be used. The allowable cut of the forest is approximately 144,000 cords per year which means approximately 5828 hectares will be cut annually. Approximately 75 percent of the forest is in the 398,760 ha Mississippi Headwaters basin and 25 percent in the 132,920 ha Big Fork River basin. For illustration purposes we apportioned the annual cut on the basis of area and considered three options (Table 3).

Table 3. Hypothetical allocation of annual timber cutting practices for the Chippewa National Forest into the Mississippi Headwaters and Big Fork basins.

Management Option	Mississippi Headwaters	Big Fork	Total Acres Cut Each Year
	- - - - - -	hectares - - - - - -	- - - - - - - -
Aspen cut and regeneration	3631	1210	4841
Aspen cut; conversion to red pine	283	128	511
Red pine cut and replanted	357	119	476
Totals	4271	1457	5828

Although the Chippewa National Forest Timber Plan was designed for eight years, the results of a 20-year program are summarized in Table 4 for the Mississippi Headwaters basin. These results indicate the increase in runoff compared to a no cutting situation. If a significant increase in timber cutting over existing levels was anticipated, such an increase should be compared to current levels of cutting in order to estimate actual changes in water yield.

FUTURE WORK

Additional options will be added to TIMWAT as we acquire more and better information relating forest growth, forest management activities and water yield. For example, relationships between forest clearcutting and changes in the magnitude of snowmelt peaks have recently been developed for northern Minnesota. Snowmelt peaks appear to change as a function of the percent of a watershed that is clearcut. Verry (1972) showed that a 30 percent clearcut diminished snowmelt peak magnitudes but analyses of subsequent years indicate that snowmelt peaks increase when 80 to 100 percent of a watershed is clearcut. A mathematical relationship which expresses clearcutting impacts on annual snowmelt peak flows is currently being developed for TIMWAT.

Table 4. Effects of the 1975 Chippewa National Forest Timber Plan on water yield for the Mississippi Headwaters basin[1] as predicted by TIMWAT.

Year	Runoff Increases Due to Cutting Options[2] 1	2	3	Total Increase	Total Runoff
	- - - - - -	- - -	- - - mm	- - - -	- - - -
1	0.9	0.1	0.2	1.2	136.2
2	1.6	0.1	0.3	2.0	137.0
3	2.1	0.2	0.5	2.8	137.8
4	2.5	0.2	0.6	3.3	138.3
5	2.9	0.2	0.7	3.8	138.8
6	3.1	0.2	0.8	4.1	139.1
7	3.3	0.3	0.8	4.4	139.4
8	3.4	0.3	0.9	4.6	139.6
9	3.5	0.3	1.0	4.8	139.8
10	3.6	0.2	1.1	4.9	139.9
11	3.6	0.2	1.1	4.9	139.9
12	3.6	0.2	1.2	5.0	140.0
13	3.6	0.2	1.2	5.0	140.0
14	3.6	0.2	1.3	5.1	140.1
15	3.6	0.2	1.3	5.1	140.1
16	3.6	0.1	1.4	5.1	140.1
17	3.6	0.1	1.4	5.1	140.1
18	3.6	0.1	1.5	5.2	140.2
19	3.6	0.1	1.5	5.2	140.2
20	3.6	0.0	1.5	5.1	140.1

[1] Total watershed area = 398,763 ha.
Annual precipitation = 643 mm
Annual runoff = 135 mm

[2] Options: 1 = cutting aspen, aspen regeneration
2 = cutting aspen, red pine regeneration
3 = cutting red pine, red pine regeneration

The long range objectives of this study are to develop linkages among several resource components for the Lake States (Figure 4). Efforts are underway to establish linkages between forest overstory and understory components which, in turn, may be related to wildlife habitat. A non-game bird model is also being linked to aspen-birch and red pine-jack pine growth models. As such a family of models becomes more complete, land managers in the Lake States may be better prepared to make multiple resource evaluations in the development of forest management plans.

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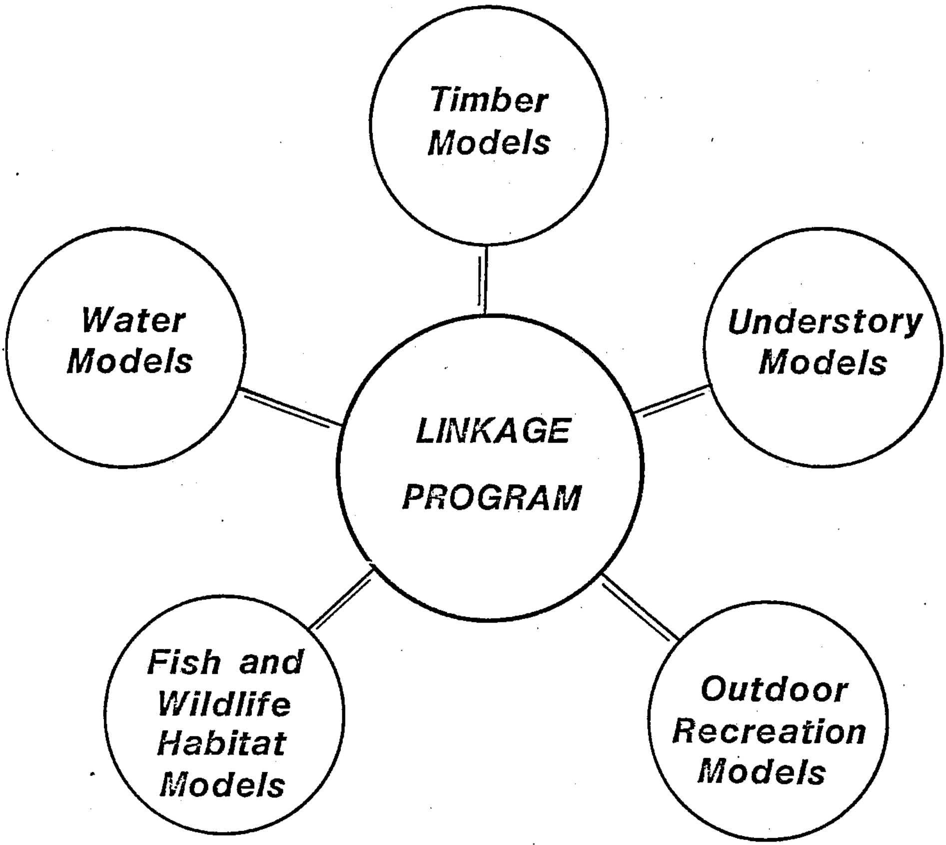

Figure 4. Framework of a multiple resource model for the Lake States.

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