Information Sciences Letters

Volume 12
Issue 5 *May 2023*

Article 40

2023

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Recommended Citation

A. Br Sinaga, J.; Tulus, T.; Mawengkang, H.; and K. M. Nasution, M. (2023) "Optimization Model of Integrated Sustainable Forest Management Planning for Hydropower Power Plant," *Information Sciences Letters*: Vol. 12 : Iss. 5 , PP -.
Available at: https://digitalcommons.aaru.edu.jo/isl/vol12/iss5/40

Inf. Sci. Lett. **12**, No. 5, 2001-2011 (2023)

Information Sciences Letters
An International Journal

http://dx.doi.org/10.18576/isl/120540

Optimization Model of Integrated Sustainable Forest Management Planning for Hydropower Power Plant

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Received: 21 Feb. 2023, Revised: 22 Mar. 2023, Accepted: 24 Mar. 2023.

Abstract: Forest management planning is placed not only on the management of timber production but also on the maintenance of forest ecosystem values, such as water conservation. Thus, the meaning of sustainable forest management has expanded from sustainable wood management to ecosystem-based multipurpose forest management. This paper discusses the need to conserve water by forests in such a way that water will flow into rivers to be used as a power source for hydroelectric power generation. The problem is then modelled as a multi-objective integer program. In this research, the model is referred to as the planning model. The planning model is filled with data and completed by appropriate procedures. The solution method is often a numerical optimization algorithm. The algorithm used to solve the model also affects the formulation of the problem, namely the type of planning model used. Based on the data analysis, the results revealed that the objectives have met in planning sustainable and integrated forest management for hydropower such as: 1) maximize the Net Present Value (NPV) of the forest within the planning horizon, 2) maximize the equity of volume harvested in each harvesting period (subject to policy constraints). In addition to 3) maximize area control criteria to determine regulated forest or age forest, 4) maximize the final inventory criteria ensuring a solution where the forest inventory will be greater than or equal to the initial inventory, 5) maximize the total carbon balance in the planning period, 6) maximize protected areas for water protection.

Keywords: Forest management, hydropower, optimization model, multi objective.

1 Introduction

Expectations for forests and forest management continue to increase and vary as a result of evolving social dynamics. Community economic, social and cultural characteristics can influence the vision of the forest in its management. In the past, the role of forests was focused on commodity purposes, but currently in various countries**,** the role of forests has transitioned or is transitioning from commodity-oriented to multi-purpose purposes. The multi-purpose goal focuses on the utilization of other aspects of the forest besides timber for improving the welfare of the community, preserving the forest environment/ecosystem, making the forest a recreational attraction, and protecting the area of water resources found in the forest.

Managing forests in a way that optimizes soil, location, terrain and the purpose of ownership will result in healthy and sustainable forests. Then forests can continue to play an important role as a hydrological function that can produce reliable, high-quality water in rivers, lakes, and wetlands that can support the needs of human populations and ecological functions. The potential of water in the river with a certain water discharge can also be used as a source of electricity that is referred to as renewable and environmentally friendly energy.

Indonesia is a country that has vast forests and of course has the potential to produce large amounts of electricity as long as stakeholders focus on forest management that utilizes the potential of water to generate electricity and not just timber production or other forest values. As stated by Josef M Ullmer as the President Director of Andritz Hydro, the potential for hydroelectric power in Indonesia is very large, namely 70,000 Mega Watt (MW) but the utilization or usage has only been utilized for less than 7%. In the future, this will become a serious challenge because integrated sustainable forest management that utilizes the potential of water to generate electricity is a real problem that involves conflicting performance measures or there are objectives that must be optimized simultaneously (economic, social and environmental).

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In this study, integrated sustainable forest management practices for hydropower plants integrate water in their management activities to ensure the sustainability of water resources, reduce the impact of floods and reduce the potential for sedimentation that can affect canals and dams. Assuming that the functional relationship between water yields and forest characteristics can be developed and the influence of various variations of forest vegetation cover can be accommodated in multi-use forest planning.

Forests play an important role in the hydrological cycle and water production**;** this is confirmed by the opinion of Cook and Spray [8] stating that forests can protect watersheds (DAS) and provide habitats for biodiversity. Forest ecosystems can also prevent and reduce flooding, help collect water in areas where flooding occurs, and maintain water supplies through dry and drought seasons. Furthermore, Syrlybayeva [17] argue that forests have a high level of infiltration and forest soil has the ability to store water, the hydrological system in forest areas can regulate water, sediment flow, and erosion [20]. This reflects the existence of a functional relationship between forest and water products, so that the multi-objective optimization model can be utilized.

Multi-objective forest management planning that integrates water certainly requires some data in its management system such as location level (stand) or forest development stage data, and forest characteristics. Destan [6] argues that in order to enable one to assess the approximation of the suitability of water yields from an area, data on forest characteristics is needed along with other important indicators such as climate norms, frequency of meteorological phenomena (rainfall intensity, duration and distribution of rainfall), and spatial attributes. Certain.

At present, there have been many models of multipurpose forest-based forest management planning developed. Multi-purpose forest management means forest management that integrates all forest values, not only in timber production but also in water production, carbon sequestration, soil protection, biodiversity, and so on [1]. Based on a literature study conducted by Syrlybayeva [17], it was stated that only a few studies focused on the application of research operations techniques with a focus on the dynamics of the process of integrating water resources into management planning and scheduling of forest harvests. During the phase of the last 20 years, in the field of multipurpose forest management, the Linear Programming technique has taken precedence over the others. In their research, Baskent and Keles [1] discussed six optimal forest management-planning strategies for forests that produce the benefits of wood, water, and carbon. The technique used is a linear programming technique. Syrlybayeva [17] produced an optimal integrated forest and water management-planning model for the forest catchment area in her research. The analysis technique used was a Decision Support System (DSS) with the ALTERFOR model framework. Furthermore, Keles and Baskent [11] integrate wood, carbon, soil erosion, and water into a computer-based forest management-planning model, using ETCAP Optimizasyon, LINGO and LINDO. Misir and Misir [13] integrated wood, water, soil erosion and volume control values into four types of forest management planning models and the technique used was goal programming, and the last was a study conducted by Baskent et al [2] integrating harvesting scheduling, wood production, water, carbon, and soil protection into a stand-based forest management planning model. The planning model developed is the DSS (Decision Support System) ETCAP (Ecosystem-based multiple use forest planning) model which consists of traditional simulations, linear programming (LP), metaheuristics and geographic information systems. Turner et al [19] applied the water yield coefficient to a linear programming (LP) model. Rowse and Center (1998) in Syrlybayeva [17] defined that applied an area control method to increase water flow to water-stressed areas. Betingger et al [3] integrated water quality measures into heuristic methods, while Chikumbo et al used water yield coefficients in the development of heuristic planning models [4]. Overall, the research findings will generally provide a choice of both the model and strategy that best suits the wishes of the decision maker.

Currently, it is accepted that every decision taken in forest planning affects several conflicting criteria namely economic, environmental, and social. As stated by Diaz-Balteiro and Romero [5] that in forest management planning, the interests of society as a whole must be pursued. Forest managers realize the need to integrate forest-planning issues within a multi-criteria framework. The most widely used multi-criteria decision-making technique is Goal Programming (GP). GP focuses on the problem of determining the optimal allocation of scarce resources to meet a given set of goals, GP also looks for a plan that is as close or efficient as possible to achieving the stated goals.

The application of GP in forestry was first presented by Field [9], following several applications of GP by Diaz-Balteiro and Romero [5]. Mendoza provides an overview of the GP formulation and specific extensions to forest planning. Tamiz et al [18] provide an overview of GP elaboration and application. Betingger et al [3] stated that the application of the GP model for the following cases: 1) Determination of production from current and future land, as well as the demand for different production; 2) Estimation of the physical capacity of the land to produce various products. In addition to 3) Analysis of complementary and competitive relationships among objectives; 4) Determination of a feasible set of desirable goals, and finally 5) Expressing the objective as a single objective function, and designing the problem formulation using the appropriate constraints. Gomez et al used the GP method to create a balance between diameter classes in Cuban forests; forests that have been heavily damaged by natural disasters and logging. Samghabadi et al [16] developed a mathematical model for sustainable forest development with strategic land use planning in the

Ramsar watershed in northern Iran, and GP was used for modelling. The results show that optimal objectives such as maximization of carbon sequestration, NPV of income, volume of stands, employment opportunities, and minimization of soil erosion can be achieved. Limaei et al [12] applied the GP model to determine the optimal timber stand or volume based on multi-criteria decision making in Iran's Shafaroud forest. Furthermore, Zengin et al [20] used the water yield model into a mixed integer goal-programming model to develop an efficient multi-use forest plan by maximizing the net benefits derived from commodity production and water production. In this research a GP model for integrated sustainable forest management planning will be developed to optimize water that can be used as a source of electricity through hydropower.

2 Method

Planning Model

In the context of planning, the model is referred to as the planning model. The planning model is filled with data and completed by appropriate procedures. The solution method is often a numerical optimization algorithm. The algorithm used to solve the model also affects the formulation of the problem, namely the type of planning model used. For example, when linear programming (LP) is used as the solution method, the forest planning problem is formulated as an LP model. If goal programming (GP) is used, the problem is formulated as a GP model.

The solution suggested by the optimization algorithm is just a candidate plan that must be carefully tested and analyzed. If it passes the test, and the sensitivity analysis shows that the solution is not too sensitive to uncertain parameters, then the solution can be recommended as a forest plan to be implemented.

The data included in the planning model is divided into two categories and comes from two sources, namely: Preference data, obtained from decision makers (laws that reflect people's preferences are included in this category). Data on production forests based on the combined use of forest inventory data and models, unit prices, etc. When LP is used to solve planning problems, information about preferences is accommodated in the model through the choice of objectives and constraint variables as well as constraint values (right side of the model). Information on forest production possibilities is contained in the coefficients of the objective and constraint functions. The coefficients tell how much the stand maintenance schedule yields or incorporates the objective or constraint variables.

With linear programming the planning problem can be modelled as follows [14]:

maximize

$$z = \sum_{j=1}^{n} \sum_{i=1}^{n_j} c_{ij}\, x_{ij} \tag{1}$$

Constraint

$$\sum_{j=1}^{n} \sum_{i=1}^{n_j} a_{ijk} x_{ij} \geq B_k \quad \text{k=1,…,}K_1 \tag{2}$$

$$\sum_{j=1}^{n} \sum_{i=1}^{n_j} a_{ijk} x_{ij} \leq B_k \quad \text{k=}K_1 + 1, \dots, K \tag{3}$$

$$\sum_{i=1}^{n_j} x_{ij} = A_j \tag{4}$$

Where z is the objective function, n is the number of stands, nj is the number of treatment alternative schedules on stand j, xij is the area of stand j which is treated according to schedule I, Bk is the constraint, K is the number of constraints, and Aj is the area of stand j. The cij coefficient indicates that as much as one hectare of stand j is processed according to schedule i to produce the objective variable, and the coefficient aijk shows that as much as one hectare of scheduling I to stand j produces the variable k. The unknown variable, the optimal value found in the optimization, namely xij treatment of the stand area with different methods. The xij variable is also referred to as a decision variable, because it is the decision maker who can decide on its value. LP problems are usually solved using standard computer software that is based on the simplex algorithm.

The formulation of the problem above allows the division of a stand into two or more sub-sectors that are treated differently. If this is not desired, the problem is formulated so that xij is defined as an integer variable, and constraint (4) is changed to:

$$\sum_{i=1}^{n_j} x_{ij} = 1 \tag{5}$$

In this formula, the decision variable is the proportion of compartments treated according to different schedules. This modification requires that the cij and aijk coefficients be changed from values per hectare to values per stand. The LP model assumes additiveness and proportionality, including; additiveness means that the total of the objective and constraint variables can be calculated by adding up the values of each variable in the maintenance schedule included in the solution. Proportionality means that the objective and constraint variables are linear functions of the decision variables.

Multi-Objective Model of Forest Management Planning

In multi-objective forest planning, the problem is modelled in such a way that the planning model accommodates several management objectives simultaneously. There are alternative ways to answer the problem of multi-objective forest planning, namely:

1. One goal is minimized or maximized through the objective function and the other objective is taken care of through constraints. This is in accordance with the use of linear programming.
2. The linear programming model is modified so that the objective function measures the deviation of several objective variables from their target level. The target level is given in another equation of the problem formulation. Strict constraints can be added to the problem formulation. This corresponds to the use of goal programming.
3. A single objective such as NPV or total cost appears in the objective function, which is augmented by the penalty function. The penalty function measures how much an additional set of objective variables deviates from its target value. The penalty function has the same units as the objective variable. Constraints can be added to the problem formulation.
4. A multi-attribute utility function is developed and used as the objective function. Constraints can be added to the problem formulation.

Formulations 1 and 2 usually use mathematical programming (LP, GP) as a solution method, while formulations 3 and 4 often rely on heuristics. However, every problem that can be solved with math programmers can also be solved with heuristics. In LP and GP operations**,** all objective and constraint variables are calculated as linear combinations of decision variables (areas or proportions treated according to a specific treatment schedule). The types of goals and constraints, the solution methods and the proper formulation of the planning model are all connected to each other. Therefore**,** the logical way to proceed with forest management planning is to know first the goals and constraints, then choose the appropriate solution method, and finally formulate the problem so that it accommodates all objectives and is in accordance with the solution technique.

When linear programming is used in multi-objective forest management planning, one of the objective variables is selected as the objective variable while the others are controlled through constraints. However, this problem formulation does not always correspond exactly to real-life problems because the constraints that refer to other objectives may not be as simple as the problem formulation suggests. Goals may have target levels and desired values but may not be absolutely necessary to achieve these values.

In order to make the planning model suitable for real life situations, an alternative problem formulation called the goal programming model has been developed [7]. In this model**,** the objective function consists of the deviation of the objective variable from its target value, which can be expressed in the following form:

$$z = \sum_{k=1}^{k} d_k^+ + \sum_{k=1}^{k} d_k^- \qquad (1)$$

Where d_k^+ shows how much the target value of goal k is exceeded (surplus), and dk- is the amount of target k deficiency (slack). The target level (bk) is given through objective constraints and one constraint per objective, namely:

$$\sum_{j=1}^{n} \sum_{i=1}^{n_j} a_{ijk} x_{ij} + d_k^- - d_k^+ = b_k \quad \text{k=1,….,k} \qquad (2)$$

Constraints and objective functions are levels of b_k that must be achieved by minimizing deviations and allowing the constraints to be flexible. If it is only less than the target, but not exceeding it is harmful, the surplus variable (d_k^+) is removed from the objective function and the corresponding objective constraints. If only it is exceeded to be avoided, variable slack (dk-) is excluded. It is also possible to multiply the deviation variable by a constant (wk and vk) that reflects the relative importance of each objective variable [10]:

$$z = \sum_{k=1}^{k} w_k d_k^+ + \sum_{k=1}^{k} v_k d_k^- \qquad (3)$$

This modification does not affect the destination constraints. Another improvement to the model is scaling the deviation variable to the same range of variation (usually between 0 and 1) so that the units of measurement do not affect the actual weights of different objectives. This scaling can be done by dividing the deviation by the largest possible value of the objective variable.

$$z = \sum_{k=1}^{k} w_k \frac{d_k^+}{Q_k^{max}} + \sum_{k=1}^{k} v_k \frac{d_k^-}{Q_k^{max}} \qquad (4)$$

Moreover, in this case the objective constraints remain unchanged. The objective programming model can be solved with the same software and algorithm as the ordinary LP model.

3 Result and Discussion

Constraints and Goals

The following constraints and goals were considered in the models.

- Area Accounting

$$\sum_{j=1}^{J} X_{zij} = X_{zi} \qquad \forall z, i \tag{1}$$

Block of constraints (1) secure that the sum of the hectares attached to each prescription has to be equal to the area corresponding to each site class and to each age class.

- Net Present Value

$$\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{j=1}^{J} NPV_{zij} X_{zij} + n_{NPV} - p_{NPV} = NPV^{*} \tag{2}$$

The target of goal (2) NPV^{*} has been obtained by maximising net present value $\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{j=1}^{J} NPV_{zij} X_{zij}$ subject to area accounting constraints (1). Therefore, NPV^{*} is an anchor value and consequently the negative deviation variable n_{NPV} is unwanted and its minimisation implies the maximisation of the net present value.

- Volume Control

$$\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{j=1}^{J} V_{zij} X_{zij} = H_l \qquad \forall l \tag{3}$$

$$H_{l+1} - H_l + n_l H - p_l H = 0, \quad l = 1, \ldots, L-1 \tag{4}$$

The volume control equations (3) and (4) impose a strict even flow of timber volume harvested each of the L cutting periods considered. Therefore, the negative $n_l H$ and the positive $p_l H$ deviation variables of goal 4 are unwanted and consequently they would have to be minimised.

- Area Control

$$X_s + n_s f - p_s f + b \quad \forall s \tag{5}$$

$$X_s = \sum_{l=1}^{2} X_{zijl} + \sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{j \in Q_j} X_{zij} \qquad \text{if } s = 1 \tag{6}$$

$$X_s = \sum_{l=2i-1}^{2i} X_{zijl} \qquad \text{if } 1 < s \le S \tag{7}$$

Eqs. (6) and (7) define the number of hectares belonging to each one of the S final age classes. If a perfectly regulated forest is wanted then the areas X_s should be equal to B for every final age class. Therefore, the negative $n_s f$ and the positive $p_s f$ deviation variables defining goal 5 are unwanted and they would have to be minimised.

- Ending Forest Inventory

$$\sum_{z=1}^{Z}\sum_{i=1}^{I}\sum_{j \in Q_k} V_{zij}^{f} X_{zij}^{f} = V_k^{f} \qquad \forall k \tag{8}$$

$$V_k^f + n_k I - p_k I = V_k^i \qquad \forall k \tag{9}$$

The ending forest inventories equations (8) and (9) establish a relationship between initial and final forest inventories. If the figures of the initial inventory are considered suitable to ensure the perpetuation of the forest harvest then the negative $n_k I$ and the positive $p_k I$ deviation variables of goal 9 are unwanted and would have to be minimised. On the contrary, if the figures of the initial inventory are considered insufficient then only the negative $n_k I$ deviation variable should be minimised.

- Carbon Balance

$$CBl = [\gamma(V^l - V^{l-1} + H_l) - CE_l] \quad \forall l \tag{10}$$

$$V^1 = \sum_{z=1}^{Z}\sum_{i=1}^{I}\left(X_{zi} - \sum_{j=1}^{J} X_{zij1}\right) V_{zi1} \tag{11}$$

$$V^2 = \sum_{z=1}^{Z}\sum_{i=1}^{I}\left(X_{zi} - \sum_{j=1}^{J}\sum_{l=1}^{2} X_{zij1}\right) V_{zi2} + \sum_{z=1}^{Z}\sum_{i=1}^{I}\left(X_{z(e1)}\sum_{j=1}^{J} X_{zij1}\right) \tag{12}$$

• • •

$$\sum_{l=1}^{L} CB_l + nCB - pCB = CB^* \tag{13}$$

Eq. (10) measures the balance of net carbon in the generic lth cutting period. This balance is expressed as the difference between the growth of the timber biomass plus the harvest minus the carbon emissions CB_l for each period. An explanation of how to calculate the carbon emissions, following the methodology proposed by [15] will be presented in the next section. Eqs. (11) and (12) provide the dynamic evolving of the structure of the forest inventories in each period, $V_{z(e1)}$ being the volume per hectare from z^{th} site class derived from harvests undertaken in first period. Finally, the target for total carbon balance CB^* is obtained by maximising $\sum_{l=1}^{l} CB_l$ subject to area accounting constraints given by Eq. (1). Therefore, CB^* is an anchor value and consequently the minimisation of the negative deviation variable nCB implies the maximisation of the total carbon captured along the planning horizon T.

- Water Protection

$$\Sigma x_{z_i}[(f_k - f_r) - Q] = Q_t \tag{14}$$

Eq. (14) ensures that target flow rate (Q_t) for river to operate HPS can be fulfilled.

Water f_k is given as

$$f_k = \frac{1}{2} S_i t^{-\frac{1}{2}} + \frac{1}{2}(k_1 + k_0)$$

water exfiltration, f_r is given by

$$f_r = \frac{1}{2} S_i t^{-\frac{1}{2}} - \frac{1}{2}(k_1 + k_0) - ME_v$$

and surface run off Q is written as

$$Q = 0.0028\, CiX$$

Algorithm

The proposed interactive algorithm consists of the following three steps.

Step 1. Determine an initial (weak) efficient solution.

Step 2. Show the solution to the decision maker (DM). If DM is satisfied with the solution, Stop: otherwise, ask the DM to specify a new reference point $\bar{f}_k$, using Analytic Hierarchy Process (AHP) and go to step 3.

Step 3. Based on the values of $\bar{f}_k$ and f_k (the last solution), solve

$$\max\ y$$

subject to

$f_k(x) - (\bar{f}_k - f_k)y \geq f_k, k \in H,$

$f_k(x) - \bar{f}_k \geq a(\bar{f}_k - f_k), k \in H,$

$f_k(x) = \bar{f}_k, k \in E$

$x \in X$

$y \geq 0$

where y is a scalar.

and to find a new intermediate weak efficient (or efficient) solution $f_k(x)$; go to Step 2.

Discussion

This section describes modelling a multi-objective program that can be used in sustainable and integrated forest management planning for hydroelectric power plants (PLTA). In forming a model, assumptions are needed that can simplify complex problems which certainly do not deviate far from reality. Next, several actions must be taken in planning forest management for hydropower.

Basic Assumptions

Translating complex problems in forest management planning into mathematical models often requires substantial simplification. As long as the simplifying assumptions do not deviate too far from reality, their effect on research results may only be marginal. Clarification of the underlying assumptions will determine the scope of application of the research.

Forest is a complex entity formed from many interactions of biophysical factors, such as soil and atmospheric conditions that cannot be changed significantly. However, it can control the composition and distribution of forest stands as well as the quantity and size of products that will be produced by the forest. Assumptions to be made relate to the operational environment and forest management intervention techniques to be applied.

The productive capacity of forests varies by location, so it is necessary to divide forestland into large areas for forest management purposes. The area and location of each growing class is clearly assumed. The area of a forest management unit can reach hundreds of thousands of hectares and in planning for forest management involves spatial and time arrangements for the treatment of certain stands, identification is required for each stand without ambiguity. This can be achieved by dividing the forest into small units, in the form of blocks and compartments with permanent boundaries.

The following describes some of the assumptions that underlie the integrated sustainable forest management-planning model for Hydroelectric Power Plants (PLTA):

1. The forest is assumed to be a normal forest.

2. Forests have been divided into broad growing classes.

3. The forest has been divided into plots that may vary in area but are uniform in terms of site class, age, composition and distribution.

4. The effect of types and conditions of vegetative cover on forest functions can be accommodated in a multi-purpose forest plan.

5. Management costs related to forest management are constant.

Actions in Integrated Sustainable Forest Management Planning for Hydropower

The model for sustainable and integrated forest management planning is based on a multi-objective approach set over a specific time period. Sustainable and integrated forest management means integrating all forest values with the aim of producing water that can be channeled into rivers, so that water with a certain debit can be used as hydropower. The following describes the objectives that must be met in planning sustainable and integrated forest management for hydropower:

a) Maximize the Net Present Value (NPV) of the forest within the planning horizon.

NPV is the value of a forest production after deducting all costs in a certain year from profits or benefits received in that year and discounted at the prevailing interest rate. A positive NPV value indicates a profit and a negative NPV value indicates a loss. Therefore, in matters of forest management planning, the objective is to maximize the NPV of the forest within the planning period.

b) Maximize the equity of volume harvested in each harvesting period (subject to policy constraints).

Equality of harvested volume and area through restrictions placed on size and extent is relatively easy to do in most models of forest planning through policy constraints.

c) Maximize area control criteria to determine regulated forest or age forest.

Volume control techniques involve a process whereby the harvest schedule is forced to 1) represent a certain level of volume over a period of time, 2) be within a range of volumes during each time period, 3) be relatively constant over a certain period of time. If a perfectly organized forest is desired, the area of the final age class in the final period will be equal to the total forest area divided by the final time period for each age class.

d) Maximize the final inventory criteria to ensure a solution where the forest inventory will be greater than or equal to the initial inventory.

The final forest inventory establishes a link between the initial and final forest inventories. If the initial inventory numbers are considered suitable to ensure continuity of forest harvest, then negative variables and positive deviations from the final forest inventory volume equal to the initial forest inventory volume must be minimized, and vice versa, if the initial inventory numbers are considered insufficient then only negative deviation variables must be minimized. .

e) Maximize the total carbon balance in the planning period.

The carbon balance is expressed as the difference between the growth of wood biomass plus crop yields minus carbon emissions for each period. The total carbon balance target is obtained by maximizing the carbon balance in each logging period.

f) Maximize protected areas for water protection.

Maximizing a water protected area means ensuring that the target flow rate for a river can operate hydropower.

4 Conclusions

The sustainable forest management model for forest around Renun river involves water preservation as well as the other criteria such as net present value, volume control, area control, and carbon balance. Goal programming technique is suitable for the management model.

Definition of model inputs

Constants

X	total forest area
K	number of forest sections $(1, \dots, k, \dots, K)$
Z	number of site classes $(1, \dots, z, \dots, Z)$
I	number of initial age classes $(1, \dots, i, \dots, I)$
J	number of prescriptions, defining a complete treatment schedule for the whole planning horizon $(1, \dots, j, \dots, J)$ (these prescriptions are defined following the model I structure (Johnson & Scheurman, 1977))
T	planning horizon
t	time unit
$L = T/t$	number of cutting periods $(1, \dots, l, \dots, L)$

t'	time span that defines the final age class
$S = T/t'$	number of final age classes $(1, \ldots, s, \ldots, S)$
Bb	total forest area divided by the planning horizon T and multiplied by the time span t' that defines the age class
X_{zi}	area corresponding to zth site class and ith initial age class
NPV_{zij}	net present value per hectare harvested from zth site class, ith initial age class at jth prescription
NPV^*	target for the net present value
V_{zil}	volume per hectare from zth site class, ith initial age class at lth cutting period
V_k^i	volume of initial forest inventory on kth section
γ	proportion of carbon contained in timber biomass
r	vector of normaliser factors for the criteria considered
w	vector of preferential weights for the criteria considered
CB^*	target for total carbon balance

Index sets

Q_j	index set of prescriptions that involve no harvests
Q_k	index set of prescriptions belonging to the kth section

Variables

X_{zij}	hectares harvested from zth site class, ith initial age class at jth prescription
NPV_{zij}	net present value per hectare harvested from zth site class, ith initial age class at jth prescription
H_l	volume harvested at lth cutting period
X_s	area belonging to sth final age class at the ending period
V_{zij}^f	volume of ending forest inventory of zth site class, ith age class at jth prescription
X_{zij}^f	hectares uncut from zth site class, ith age class and jth prescription at the ending period
V_k^f	volume of ending forest inventory on kth section
V^l	volume of forest inventory at the end of lth cutting period
X_{zijl}	hectares harvested from zth site class, ith initial age class, jth prescription at lth cutting period
CB_l	carbon balance at lth cutting period
CE_l	carbon emission at lth cutting period

Deviation variables

n_{NPV}, p_{NPV}	negative and positive deviation variable for the net present value criterion
$n_l H, p_l H$	negative and positive deviation variables for the volume control goal $(l = 1; \ldots; L-1)$
$n_s f, p_s f$	negative and positive deviation variables for the area control goal $(\forall s)$
$n_k I, p_k I$	negative and positive deviation variables for the ending forest inventory goal $(\forall k)$
nCB, pCB	negative and positive deviation variable for the total carbon balance goal

Conflict of interest: The authors declare that there is no conflict regarding the publication of this paper.

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