



WATERSHED MANAGEMENT PROGRAMME PLANNING: A LINEAR PROGRAMMING APPROACH

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ABSTRACT: The paper explores the importance of planning in watershed programs crucial for economic growth and citizen welfare. It focuses on using linear programming (LP) for effective watershed management, applying hypothetical data to a model. Results indicate successful planning for annual crops and agroforestry, yielding 1,000,000 and 500,000 products respectively, maximizing profit constrained at 10,500,000 products. However, forestry development units were underutilized, yielding no products over five years, highlighting poor planning. The LP model offers potential for regulatory authorities managing forest lands, aiding in private sector engagement and investment terms.

Keywords: Watershed, Management, Planning, Linear Programming

INTRODUCTION

In an agriculturally prosperous economy like Nigeria, the disparities in forest resources and economic conditions among regions are well-known. Some states are more dynamic and prosperous, while others develop slowly or remain stagnant over long periods. If these disparities are left unchecked, they can negatively impact the overall economic development of the nation. However, such disparities are inevitable due to varying climatic and geographical conditions, as well as differences in the quantity and quality of indigenous forest resources in each state.

Watershed development is vital for national growth as it provides essential goods and services to society, including forest products, wildlife, recreational value, agricultural products, water supply, climate stability, and pollution control. A watershed is defined as the surface area drained by a stream or body of water and its tributaries, encompassing both social processes and patterns (Hamilton and King, 2019).

The interaction between physical, biological, and socio-economic factors in a watershed is complex, necessitating specific attention for proper management and planning to minimize adverse impacts. Upland watershed development influences downstream communities, affecting their well-being. Therefore, watershed management goals must be pursued in an environmentally and economically feasible and technically acceptable manner (Brooks, 2019).

Mathematical programming systems, particularly Linear Programming (LP), have been developed as effective tools for solving forest resource planning problems. In forestry, LP is widely used for timber plantation scheduling and agroforestry management (Zira et al., 2020). However, the application of mathematical programming in watershed planning is still underdeveloped. Watershed management has yet to be fully appreciated in Nigeria. To address this gap, Anderson et al. (2018) developed a watershed management program using a linear programming approach. This paper reviews the theory and algorithmic methods for watershed management planning using hypothetical data.

FACTORS CONSIDERED

Institutional Factors

Institutional factors are critical for assessing the success and sustainability of watershed management activities. The effectiveness of watershed management in any country hinges on national policies, public awareness, local government structure, land use and watershed management laws, community culture, and the education level of the population (Evan, 2019).

Biophysical Factors

Biophysical factors estimate the capacity of a watershed to meet the demands for goods and services. These include climate, soil type, vegetation, drainage patterns, and stream systems. This data forms the foundation for preparing effective watershed management plans (Kidd *et al.*, 2018).

Technical and Economic Factors

Technical and economic factors are also essential in formulating a watershed management plan. These factors, interrelated with institutional and biophysical characteristics, include existing technology, cropping systems, soil management practices, land use changes, and resource development. Duckworth *et al.* (2015) emphasized the importance of economic criteria in assessing watershed benefits, suggesting that integrating watershed resources is vital for a feasible management plan. Watershed ecosystems are dynamic, necessitating adaptable strategies and goals.

Watershed Management Planning Process

In Nigeria, explicit watershed management planning is rare, although state-level forest management planning exists, undertaken by various local government areas. Agricultural development often involves large drainage and river basin authorities like Upper Benue and Lower Benue. These river basins have historically benefited farm families and provided employment. However, proper land-use planning within a river basin framework is crucial for effective natural resource management, particularly water quality.

A watershed plan should be based on topographic, soil, and land-use capability data, slope intervals, erosion and site degradation, vegetation cover, and other information from aerial photos/maps. By overlaying and matching these maps, detailed information on drainage patterns, stream systems, soil types, depths, slope degrees, soil management intensity, degradation/erosion stages, types of native vegetation, and potential land development can be obtained. Satterland (2015) outlined the principal procedures for watershed management planning and applications:

1. Recognition of need and formulation of tentative management objectives
2. Inventory of basic information, including material resources and human/cultural characteristics
3. Input of technical knowledge and human understanding
4. Analysis of inventory information
5. Plan formulation
6. Implementation of the plan
7. Continuous monitoring and evaluation

WATERSHED MANAGEMENT MODEL

Linear Programming Model Formulation

The core of the mathematical model involves identifying variables and expressing the objective and constraints as mathematical functions of these variables (Taha, 1982). Five steps are outlined to provide a framework for solving these problems:

Problem Formulation

Watershed management planning involves formulating actions that manipulate natural, agricultural, and human resources, considering socio-economic and institutional factors to achieve objectives (Brooks, 2017). The primary challenge in watershed planning is synchronizing actions and activities to produce an optimal mix of products or services without degrading the watershed.

Model Assumptions

To establish a framework for solving watershed planning problems, the following assumptions are made: (a) The watershed management area is treated as an economic unit, allowing the use of the maximized net present value (NPV) criterion as the primary objective. (b) Land is considered homogeneous in quality. (c) Watershed products and services, including agricultural products, must satisfy local demand and permissible erosion levels. (d) Proposed alternatives for cropping and farming systems must be feasible and acceptable. (e) Products/services from each land unit (LU) and land development unit (LDU) are based on predicted yields. (f) The model focuses solely on forest production and annual allowable cut, excluding operational costs. (g) A planning period of five years is considered for watershed management development.

Definition of the Objective Function

Two feasible objective functions are: (a) Maximize the total mix of products and services from watershed development to achieve optimal expected NPV. (b) Minimize the total erosion rate.

Definition of Constraints

Constraints on watershed development variables include: (a) Minimum or maximum levels of product/service to satisfy demand annually during the planning period. (b) Maximum allowable erosion rates per year during the planning period. (c) Available budget per year during the planning period. (d) Maximum available area of watershed resources. (e) Non-negative decision variable constraints

LP Model constructions

(a) Variable: To determine the end result of watershed management planning, the variable of the model can be defined as; X, Y, P, R, C, K, E, A, B, and d.

(b) Objective function

$$\sum_i^n \sum_j^n \sum_k^n R_{qij} x_{ijk} \quad (1)$$

$$\sum_i^n \sum_j^n \sum_k^n E_{ij} x_{ijk} - d \sum Y_{pk} \quad (2)$$

Subject to constraints

$$\sum_i^n \sum_j^n \sum_k^n P_{qij} x_{ijk} \text{ for } K=1,2, \dots, 5 \quad (3)$$

$$\sum_i^n \sum_j^n E_{ij} x_{ijk} \leq E_K \text{ for } K=1,2, \dots, 5 \quad (4)$$

$$\sum_j^n \sum_k^n C_{ij} x_{ijk} \leq C_K, \text{ for } K=1,2, \dots, 5 \quad (5)$$

$$\sum_P^n \sum_K^n C_P Y_{PK} C_{jk} \text{ for } K=1,2, \dots, 5 \quad (6)$$

$$\sum_i^n \sum_j^n x_{ijk} \leq A_{ij} \text{ for } j=1,2, 3 \quad (7)$$

$$\sum_i^n Y_{PK} \leq A_{ij} \text{ for } j=2, 3 \quad (8)$$

$$p \leq H \text{ for all } P=1,2 \quad (9)$$

$$x_{ijk} Y_{PK} \geq 0 \text{ for all } i,j,k,p \quad (10)$$

Where:

H_{ijk} = Area (ha) in LU_i under LDU_j at planning year K^{th}

Y_{pk} = Total catchments area developed for check dam p^{th} at year K^{th}

P_{qij} = Products q^{th} given by LU_i under LDU_j

R_{qij} = Total NPV per ha associated with product q in LU_i under LDU_j at plan year K^{th} .

C_{ij} = Cost for development activities under LU_i in LDU_j

C_{iP} = Cost for building check dams for catchments area Y_p .

K_{qk} = Total products demand per year plan k^{th}

E_k = Total permissible erosion at year plan k^{th}

c_k = Total maximum cost for the k^{th}

C_{ik} = Total maximum cost for building check dam at year k^{th}

A_j = Total area LDU_j

H = Total catchments development for building check dams.

d = Constraints of decreasing erosion due to check dams

(Zira and Ghide, 2013).

Information and Data

Land Development Unit (LDU) and land unit (LU)

Watershed areas are grouped into three land development units (LDU), viz: LDU

(1) for annual crop culture (ACC)

(2) for agro-forestry culture (AFC)

(3) for forestry culture (FOC).

LDU is assigned from maps overlaid of topographic soil type, and land used with the use of slope range.

Land Unit (LU) is determined and measured by overlaying maps of topography, slope, soil type and watershed boundary map (Scale 1: 10,000). To differentiate LUs, slope range 0-10%, 11-20%, 21-30%, 40-50% and 50% and above of soil group types (S_1 S_2 S_3 S_4 ---- S_n) should be determined.

Watershed products and services function

Mathematically, the production functions form watershed products/services with resources can be started as:

$$P_1 = f(X_{11}, X_{12}, \dots, X_{1j}, X_{1n}) \quad (11)$$

$$P_2 = f(X_{21}, X_{22}, \dots, X_{2j}, X_{2n})$$

$$P_j = f(X_{j1}, X_{j2}, \dots, X_{j1}, \dots, X_{jn})$$

$$P_m = f(X_{m1}, X_{m2}, \dots, X_{mj}, \dots, X_{mn})$$

Where:

P_1 = any watershed products or services from any resource

X_j = any watershed resources product P under criteria 0-30% (ANC) and 50% up (FOC) (Curtis *et.al.*, 2014)

Soil Erosion Prediction function

Prediction of soil erosion rate on present land use (before development) and after development with alternative plan is predicted by the universal soil loss equation (Dargavel, 2019) ton/ha/ year

$$E = F(R, K, L, S, C, P)$$

E = erosion loss in ton/ha/year

R = rainfall factor (Index erosivity)

K = Soil erodibility factor

LS = slope length and slope gradient factor

C = cropping management factor

P = erosion control practices.

Net Present Value (NPV)

Net Present Value (NPV) is an economic criterion used to determine which alternative management input and soil conservation measure will yield the optimal profit after watershed development. It is calculated using the following formula:

$$NPV = \frac{\sum Q_t(1+r)^t - C_0 + \sum C_t(1+r)^t}{(1+r)^t}$$

Where:

Q_t = Cash inflow at the years

C_t = Cash outflow at the years

C_0 = Cost of investment at 0 year

i = Interest rate (cost of capital)

t = year

Problem Formulation

The Malgwi farm, located in Hawul, obtained a loan of ₦5,500,000 from an agricultural bank for investment opportunities. The farm management recommends developing three watershed development units: Annual Crop Culture, Agroforestry Culture, and Forestry Culture, to optimize yield. Out of the loan, ₦4,000,000 is allocated for development activities and ₦1,500,000 for building a check dam.

The total catchment area for the check dam is 200,000 hectares, with 50,000 hectares allocated for permissible erosion control in the Agroforestry development unit. Two check dams are built for the watershed development units – one for forestry and the other for annual crops. After five years, the farm produced 8, 5, and 10 watershed products from the three units, respectively.

The management wishes to determine the production plan that maximizes profit for the farm

Objective function Max $z = 8X_1 + 5X_2 + 10X_3$

Subject to $2X_1 + 3X_2 + X_3 \leq 4,000,000$ (cost for development activities in LU under LDU)

$X_1 + X_3 \leq 1,500,000$ (cost for building check dam in LU under LDU)

$2X_1 + X_2 + 4X_3 \leq 200,000$ (Total catchments area for Check dam)

$X_2 \leq 50,000$ (Permissible erosion)

$X_1, X_2, X_3 \geq 0$ (non-negativity)

Watershed Management Programme Planning

Table 1. Watershed Product initial table

Solution Variable	Production			Slack Variables				Solution Quantity
	X ₁	X ₂	X ₃	S ₁	S ₂	S ₃	S ₄	
S ₁	2	3	1	1	0	0	0	4,000,000
S ₂	1	0	1	0	1	0	0	1,500,000
S ₃	2	0	4	0	0	1	0	200,000
S ₄	0	1	0	0	0	0	1	50,000
Z	-8	-5	-10	0	0	0	0	0

Table 2. Watershed Product second table

Solution Variable	Production			Slack Variables				Solution Quantity
	X ₁	X ₂	X ₃	S ₁	S ₂	S ₃	S ₄	
S ₁	1 $\frac{1}{2}$	3	0	1	0	-1/4	0	3,500,000
S ₂	$\frac{1}{2}$	0	1	0	1	-1/4	0	1000,0000
X ₃	$\frac{1}{2}$	0	1	0	0	$\frac{1}{4}$	0	50,000
S ₄	0	1	0	0	0	0	1	50,000
Z	-3	-5	0	0	0	$\frac{1}{2}$	0	500,000

Table 3. Watershed Product third table

Solution Variable	Production			Slack Variables				Solution Quantity
	X ₁	X ₂	X ₃	S ₁	S ₂	S ₃	S ₄	
S ₁	1 $\frac{1}{2}$	0	0	1	0	-1/4	3	2,000,000
S ₂	$\frac{1}{2}$	0	0	0	1	-1/4	0	1,000,000
X ₃	$\frac{1}{2}$	0	1	0	0	$\frac{1}{4}$	0	50,000
X ₂	0	1	0	0	0	0	1	50,000
Z	-3	0	0	0	0	2 $\frac{1}{2}$	5	750,000

Table 4. Watershed Product final table

Solution Variable	Production			Slack Variables				Solution Quantity
	X ₁	X ₂	X ₃	S ₁	S ₂	S ₃	S ₄	
S ₁	0	0	-3	1	0	-1	-3	2,000,000
S ₂	0	0	-1	0	1	-1/2	0	500,000
X ₁	1	0	2	0	0	$\frac{1}{2}$	0	1,000,000
X ₂	0	1	0	0	0	0	1	500,000
Z	0	0	6	0	0	4	5	10,500,000

DISCUSSIONS

The study findings indicate that watershed development units for annual crops and agroforestry were effectively planned and managed, yielding 1,000,000 and 500,000 products respectively. This combination maximizes profit within the constraints of producing 10,500,000 units. However, resources allocated for forestry development were underutilized, with ₦2,000,000 and ₦500,000 remaining, represented by slack variables S1 and S2. This underutilization suggests inadequate planning, with the tree area ratio below one, indicating underdeveloped land not meeting cutting standards.

Soil erosion was significantly reduced through construction activities like check dams and other development efforts in watershed management. The model facilitates optimal land allocation and identifies soil conservation methods to minimize erosion rates.

Linear programming (LP) stands out as a vital tool in operations research, particularly in forestry management such as timber harvesting scheduling, plantation scheduling, and resource allocation. Previous studies emphasize its versatility and applicability, notably in solving cut schedule problems and industrial forest management.

Various approaches have been explored in forest-level planning, though mathematical programming systems remain underutilized in watershed management planning in Nigeria. Early adoption by Heady (1966) highlighted LP's potential to maximize net revenue in watershed development planning.

CONCLUSION

A watershed is not merely a hydrological unit but an ecosystem integrating natural and human resources. LP offers robust capabilities in assessing watershed products' competitive strength when well-planned, identifying strategic issues and opportunities for farmers.

This paper presents foundational concepts and methods applicable across diverse watershed management planning scenarios, offering a structured approach adaptable to forestry sectors in developing economies.

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