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A multi-objective programming approach for optimal management of the Río Caonillas watershed in north-central Puerto Rico

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Abstract
In hydrologic watershed analysis there is a strong relationship between land use and total nutrients loads carried by runoff into receiving water bodies. Puerto Rico as other territories of the USA regulated by the Environmental Protection Agency (USEPA) must comply with water quality standards imposed by both the USEPA and the Puerto Rico Environmental Quality Board (PREQB). This investigation applies a multi-objective approach to find the best combination of land use and land management practices in the Río Caonillas watershed in North Central Puerto Rico that meets the requirements of the USEPA in terms of nutrient loadings such as Total Phosphorus (TP), Dissolved Phosphorus (DP) and Total Kjeldahl Nitrogen (TKN). The goal programming approach was used as method of analysis in the investigation. The results showed that two of the three goals, corresponding to Total Phosphorus (TP) and Dissolved Phosphorus (DP) were reached using the mentioned method. The Total Kjeldahl Nitrogen (TKN) exceeds the EPA limits about 3,394.27 kg in the analysis year.

Keywords
Total loads; land use, multi-objective, optimization, nutrients.

1. Introduction

Puerto Rico as well as other states of the Nation is in the process of developing Total Maximum Daily Loads (TMDL's) for lakes and rivers listed as impaired waters (303 (d) list) by the USEPA and the local PREQB. As part of this effort, this work is presented in order to evaluate the Caonillas watershed, in the north-central area of Puerto Rico to determine the best possible combination of the land use currently present in the watershed and that meets the allowable nutrient loading criteria for water quality.

Many research programs in the field of water resources and system planning have focused on the goal that pursues the sustainable land development, water resources conservation, and water quality management by using deterministic multi-objective programming techniques (Chang et al, 1995). For example Goicoechea and Duckstein (1976) illustrated the use of multi-objective programming models in a watershed land management project without considering environmental factors. Van and Nijkamp (1976) presented a multi-objective decision model for optimizing regional development, environmantal quality control and industrial land use. Das and Haimes (1979) applied multi-objective optimization techniques in a river basin planning project. Two broad based planning objectives considered in their project are: economic development and environmental quality. Both impacts of point and nonpoint source pollutants on water quality were evaluated in its various land management scenarios. Later Ridgley and Giambelluca (1992) applied a water balance simulation model for calculating groundwater recharge as it varies with land use in a multi-objective programming framework.

Beck (1987) explained that the random character of the natural processes governing water resources, the estimation errors in parameters of water quality models, and the vagueness of planning objectives and constraints are all possible sources of uncertainty. Chang et al. (1995) incorporates the uncertainty in their analysis using a fuzzy multi-objective approach.

2. Study area

This study focuses on the Rio Caonillas watershed located in the municipally of Jayuya, in the north-central mountain region of Puerto Rico. Runoff from this watershed discharges in the Caonillas reservoir (Figure 1). At the outlet (USGS code 50026025), the watershed has a drainage area of 98 km^2 (38 mi^2), a basin slope of 0.3751 m/m (ft/ft) and average annual precipitation (1910 - 2001) of 1930 mm (76 in) recorded at the Jayuya weather station. Mean daily streamflow for Río Caonillas watershed at Paso Palma is 2.83 m^3/s (100 cfs) (USGS code 50026025, October 1995 to September 2001). Elevation in the study area ranges from 300 to 1,338 m (984.2 to 4,389.8 ft). Cerro Punta at 1,338 m is the highest elevation in Puerto Rico. Present land use distribution in the watershed is 66% forest land, 21% rangeland and 6.9% agricultural land. Coffee and banana are the principal crops in the study area. Crops cultivated in the watershed are established without soil conservation practices (ground truthing and personal communication with agricultural extensions of the Municipality of Jayuya).

Soils within Río Caonillas watershed are deep without restricted layers, very steep, varying from well to excessively well drainage conditions, and approximately 86% developed on cretaceous plutonic rocks. Sixty six percent and 27% of soils belong to the hydrologic group B and C, respectively.

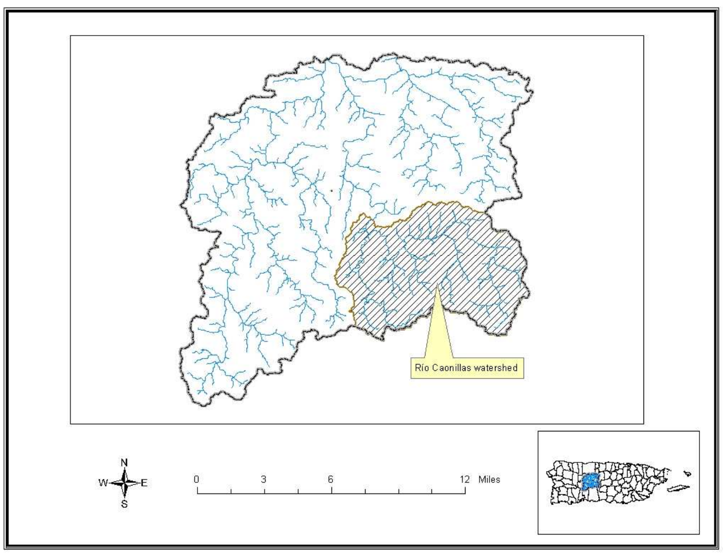

Figure 1: Río Caonillas watershed localization inside Río Grande de Arecibo watershed. (Díaz, 2004)

3. Methodology

The method used to solve the multi-objective optimization problem is called "goal programming". This method is used in situations where the system may have multiple (possibly conflicting) objectives. In such situations, it may be impossible to find a single solution that optimizes the conflicting objectives. Instead, we may seek a compromise solution based on the relative importance of each objective. The main idea of the method is to convert the original multiple objectives into a single goal and the resulting model yields what is usually referred to as an *efficient solution* because it may not be optimum with respect to all the confliciting objectives of the problem.

4. Model formulation

A deterministic multi-objective programming model was formulated based in five categories of land use (variable decisions), including forest, agriculture land, urban, pastures and range land. The information, incorporated into the optimization objectives in this study is related to impacts to water quality as a result of specific discharges of total phosphorus (TP), dissolved phosphorus (DP) and total kjeldahl nitrogen (TKN) in runoff from stakeholders-land users.

4.1 Data

Associated data to land use export coefficients was compiled for the multi-objective model solved in this study. A land use export coefficient is an estimate of the mass loading of a specific nutrient exported from a particular land use in one year (Kg ha^{-1} yr^{-1}). Typically export coefficients are derived from field data collected in past research and monitoring studies.

The export coefficients used in this study were taken from USEPA (1980), "Modeling phosphorus loading and lake response under uncertainty: A manual and compilation of export coefficients". Table 1 show the values used in the multi-objective optimization:

Table 1: Mean export coefficients

Nutrient	Land Use	Mean Export Coefficient (kg/ha*yr)
Total Phosphorus (TP)	Forest	0.236
	Agriculture	1.134
	Urban	1.91
	Pasture	1.5
	Rangeland	300.7
Dissolved Phosphorus (DP)	Forest	0.1
	Agriculture	0.4536
	Urban	0.8595
	Pasture	0.85
	Rangeland	210.2
Total Kjeldahl Nitrogen (TKN)	Forest	2.86
	Agriculture	16.53
	Urban	9.97
	Pasture	8.65
	Rangeland	3110.7

In order to achieve the model formulation, the USEPA standards limits were selected as the goals of the multi-objective optimization. In this sense USEPA limits are the maximum permitted loads from nutrients, in water body receptors.

To determine the maximum load values, the maximum concentration is multiplied by the mean daily flow of the analyzed watershed. Equation (1), show the mathematical procedure:

$$Total\, mximum\, load = Q_{mean\, daily} * Maximum\ permitted\ concentration * conversion\ factor \qquad (1)$$

Table 2, show the maximum total loads for each nutrient.

Table 2: Mean export coefficients

Nutrient	Maximum Concentration* (mg/L)	Maximum Load (kg/yr)
Total Phosphorus (TP)	0.1	10,000
Dissolved Phosphorus (DP)	0.06	6,000
Total Kejdahl Nitrogen (TKN)	1	100,000

*Environmental Protection Agency, Water Quality Criteria (1986)

4.2 Final model

Using the above data, the final multi-objective model, includes three objectives, five decisions variables and ten restrictions. The proposed three objectives are defined as follows:

$Z_1 =$ The objective function of total discharge of phosphorus, (TP);
$Z_2 =$ The objective function of dissolved discharge of phosphorus, (DP);
$Z_3 =$ The objective function of total kjeldahl nitrogen discharge, (TKN).

And the five decision variables are:

$X_1 =$ The optimal area reserved for forest conservation.
$X_2 =$ The optimal area allowed for agricultural development.
$X_3 =$ The optimal area assigned for urban use.
$X_4 =$ The optimal area reserved for pastures.
$X_5 =$ The optimal area reserved for range land.

Description of each of the ten restrictions considered in the final problem formulation, are as follows:

Restriction 1: The maximum area allowed for developing various land use programs is 9,8841.95 ha in this watershed, which is equal to the watershed area minus the surface area of the reservoir.

Restriction 2: Due to the reserved area as forest. Actually this area is the 66% of the total area.

Restriction 3: Associated to the minimum agriculture area. Actually this area is the 7% of the total area.

Restriction 4: Associated to urban development. In Río Caonillas watershed, the urban area is estimated around 5.6% approximately.

Restriction 5: Minimum area assigned to non-controlled pastures.

Restriction 6: Minimum area assigned to rangeland.

Restriction 7: This restriction is associated with the Environmental Protection Agency (EPA) standards. The restriction is a function of the maximum permitted value of total phosphorus (TP) in water bodies receptors.

Restriction 8: Similar to the above case, this restriction is associated with the EPA maximum permitted value of dissolved phosphorus (DP) in water body receptors.

Restriction 9: Associated to the maximum total Kjeldahl nitrogen (TKN) amount in accordance to EPA standards of water quality.

Restriction 10: Nonnegative constraints.

The final mathematical model is:

$$Min\ \ Z_1(x) = 0.236X_1 + 1.134X_2 + 1.91X_3 + 1.5X_4 + 300.7X_5$$
$$Min\ \ Z_2(x) = 0.1X_1 + 0.4536X_2 + 0.8595X_3 + 0.85X_4 + 210.2X_5$$
$$Min\ \ Z_3(x) = 2.86X_1 + 16.53X_2 + 9.97X_3 + 8.65X_4 + 3110.7X_5$$

subject to:

1- $X_1 + X_2 + X_3 + X_4 + X_5 + X_6 = 9{,}841.95\ ha$

2- $X_1 \geq 6{,}495\ ha$

3- $X_2 \geq 688.93\ ha$

4- $X_3 \geq 492\ ha$

5- $X_4 \geq 30\ ha$

6- $X_5 \geq 20\ ha$

7- $0.236X_1 + 1.134X_2 + 1.91X_3 + 1.5X_4 + 300.7X_5 \leq 10{,}000$

8- $0.1X_1 + 0.4536X_2 + 0.8595X_3 + 0.85X_4 + 210.2X_5 \leq 6{,}000$

9- $2.86X_1 + 16.53X_2 + 9.97X_3 + 8.65X_4 + 3110.7X_5 \leq 100{,}000$

10- $X_1,\ X_2,\ X_3,\ X_4,\ X_5, \geq 0$

5. Optimization results and discussions

To solve the multi-objective problem, the LINDO software was used. LINDO is a program to solve linear, integer and non linear optimization problems. The method used was "weighting method", and the weight assigned to each of the three goals was the same. That reflects that in our case, total phosphorus, dissolved phosphorus and total Kjeldahl nitrogen had the same importance in terms of maximum permitted load.

From the results, two of the three goals were reached in the analysis. The TKN goal was not reached, and it exceeds the maximum value by 3,394.3 kg in the year of analysis. Table 3 and 4 reflect the optimal land use areas obtained from the multi-objective linear programming and the goals reached levels.

Table 3: Optimal solution of multi-objective analysis using weighting method

Land use	Optimal land use area (ha)
Forest	8,611.02
Agriculture	688.93
Urban	492.00
Pastures	30.00
Rangeland	20.00

Table 4: Goals reached levels using weighting method

Goal	Reached level (%)
Total Phosphorus (TP)	100
Dissolved Phosphorus (DP)	100
Total Kjeldahl Nitrogen (TKN)	Exceded*

*TKN goal was exceeded by 3,394.3 kg

As a part of this work, results validation was conducted using a different type of solution method. The second method used was the "preferential method". In this case a preferential goal order was established, beginning with nitrogen goal as the first preference and then total phosphorus and dissolved phosphorus in second and third order, respectively. The results were the same as those obtained with the weighting method.

In multi-objective optimization analysis, it is almost impossible to reach all the proposed goals. In this sense obtain a single solution that optimizes the conflicting objectives is very difficult. The obtained results in this work reflect a good solution, because two of the three goals were reached and the third goal associated with nitrogen (set at 100,000 kg TKN) was exceeded by merely 3,394.3 kg.

A minimization problem was outlined, and for this reason the optimal areas obtained in Table 3 make sense. The optimization algorithm tries to search a minimum value to reach the goals. In the forest case, this land use presented the minimum export coefficients for the three nutrients goals and for this reason it has the higher permitted area.

6. Conclusions

Section 303 (d) of the Clean Water Act (1977) requires jurisdictions to develop Total Maximum Daily Loads (TMDL's) for waters that remained polluted after the application of technology-based requirements. The present paper shows that the multi-objective optimization analysis can be an effective tool in the development of TMDL's and setting up priorities in terms of limited economic resources to clean up polluted streams and lakes.

Likewise, in watershed management the multi-objective optimization can be an useful tool in determining the minimum territorial extension of both beneficial stakeholders (land users) and those that although are risky operations are needed.

The results obtained in this work show that in a multiple objectives problems, it is impossible to reach all the proposed goals, but reaching an optimal solution (acchieving the largest number of set goals) is feasible and more realistic.

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