Multi-Objective Optimization Approach For Land Use Allocation Based On Water Quality Criteria

Luis R. Pérez-Alegría, Ph.D., P.E.
University of Puerto Rico, Mayaguez, Puerto Rico, USA, luisr.perez1@upr.edu

Cristhian Villalta-Calderón, Ph.D.
Policetnic University of Puerto Rico, San Juan, Puerto Rico, USA, cristhianvillalta@gmail.com

ABSTRACT

A ten year (1995-2005) continuous hydrological simulation analysis was conducted in a tropical watershed to predict nutrient (total nitrogen and total phosphorous) and suspended sediments and relate mass loadings to landuse. Nutrient and sediment export coefficients were generated for all watershed stakeholders (landuse). The model used is Hydrological Simulation Program Fortran (HSPF) developed by the USEPA and contain in the suit of BASINS. A separate interface was developed to feed the results from the HSPF model into an optimization analysis module that creates future mass loadings as a result of propose landuse changes. Results from the optimization analysis are used to predict future water quality of receiving streams as a result of several hypothetical Management-development scenarios proposed for the study watershed. A total of six different hypothetical scenarios were evaluated reflecting possible conditions in the future growth pattern in the watershed in the time study horizon (year 2025). Multi-objective optimization analysis techniques were used to evaluate best possible scenario in terms of satisfying stakeholders need and maintaining water quality standards in river outlets and estuaries.

Findings of this research will provide the base work to find solutions to difficult issues related to land use planning and allocation while at the same time maintaining water quality and quantity.

Keywords: Multi-objective optimization, water quality, land use planning, nutrients, HSPF.

1. INTRODUCTION

Multi-objective optimization linear programming (MOLP) deals with several independent objectives and solves them simultaneously. It may be impossible to find a single solution that optimizes the conflicting objectives for a particular situation. Instead, a compromise solution based on the relative importance of each objective is searched and simultaneously optimized for the conflicting objectives. Pareto optimal solution is a commonly used term in multi-objective optimization and refers to solutions equally good with respect to others.

A Pareto optimal set of solution is such that when we go from any one point to another in the set, at least one objective function improves and at least one other worsens (Yee et al., 2003). Neither solution dominates over each other. All the sets of decision variables on the Pareto front are equally good and are expected to provide flexibility for the decision maker. Normally, the decision about “what the best answer is” corresponds to the so-called decision maker (Coello, 1999).
Classical and evolutionary algorithms are two main groups of solution methods for handling MOLP problems. Classical methods have been around for at least the past forty years. During those years numerous algorithms were developed by researchers. Although the origins remount to the late 1950s, the evolutionary algorithms started to receive significant attention during the last decade.

In water resources problems as well as in many modeling situations, it is unreasonable to assume that the coefficients or functions in optimization problems are deterministically fixed values. Most real-world situations are characterized by limited to no data. Often, data is difficult to obtain, relies on estimates and is subject to changes. As a result, these combinations create uncertainty in the analyzed system and therefore deterministic optimization techniques are not sufficient to model uncertainties sources associated with variation in model parameters.

Several methods have been used to tackle uncertainty in optimization problems. Some of the methods used are the fuzzy multiobjective optimization, stochastic multiobjective optimization and multiobjective linear programming with interval coefficients. In the fuzzy multiobjective optimization method, it is important to define a so called membership function that simulates a probabilistic distribution in variable coefficients. In the stochastic method a probability distribution are needed and in the linear programming with interval coefficients method only a range of variation for each parameter is needed.

1.1 MULTI-OBJECTIVE OPTIMIZATION APPLIED TO WATER RESOURCES

In water resources multi-objective optimization and system planning, researchers 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). Goicoechea and Duckstein in 1976 illustrated the use of multi-objective programming models in a watershed land management project without considering environmental factors. In that same year, Van and Nijkamp (1976) presented a multi-objective decision model for optimizing regional development, environmental 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 were: economic development and environmental quality. Both impacts of point and nonpoint source pollutants on water quality were evaluated in various land management scenarios. 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 stated 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 (Beck, 1995). In 1995 and 1997, Chang incorporated the uncertainty in the analysis using a fuzzy multi-objective approach for the evaluation of sustainable management strategies of optimal land development in the analyzed reservoir watershed. (Chang et al., 1995; and Chang et al., 1997).

Wang and Huang in 2004 uses Inexact-fuzzy multi-objective optimization approach (IFMOP) to solve a problem in Lake Erhai basin, China (Wang, 2003).

2 METHODOLOGY
The study was conducted at a tropical watershed in north-central Puerto Rico. Multiple scenarios were evaluated to obtain sustainable strategies for optimal land use growth in the Río Grande de Arecibo using a Multi-objective Linear Programming Approach (MOLP). Two different algorithms in combination with several hypothetical scenarios were used as solution methods, reflecting spatial, socio-economic, physical and political factors.

2.1 Multi-objective Optimization Solution Methods

Two different methods were used to solve the land use planning scenarios. The first method is based on the Goal Programming method developed by Charnes in 1955, specifically the weighted goal programming method. The second method is the Goal Attainment method used by Gembicki in 1975. This implies the construction of a set of goal values for the objective functions.

It is well known that uncertainty plays an important role in optimization problems, therefore based on the results from the water quality simulation in HSPF, the land use export coefficients intervals obtained were introduced into the MOLP analysis to reflect the stochastic nature of the problem. Land use export coefficients intervals responded to the results from a ten years continuous simulation (1995-2005) using HSPF. Outputs from HSPF reflected the variability of the response to the number of parameters in the model and the different uncertainties in the export coefficients. Factors like sub-watershed physical characteristics (slope, area); hydrometeorological behavior (rain spatial and temporal distribution) were reflected in the export coefficients intervals from a calibrated hydrologic, sediments and water quality models.

The optimization model developed in this project is robust because it included the uncertainties and stochasticity of the land use allocation system analysed in this project. The analysis which included the uncertainties, gave a strong developed optimization model because it considers the stochasticasticity in the analyzed system.

2.2 Goal Attainment Algorithm Description

The multi-objective optimization approach minimizes a set of objectives simultaneously. One formulation for this problem which was implemented in this research is the goal attainment problem from Gembicki (1975).

The optimization strategy of Goal Attainment method allows the objectives $F(X) = \left\{ f_1, f_2, \ldots, f_m \right\}$, to be under or over-achieved according to the preset design goals $\left\{ f_1^*, f_2^*, \ldots, f_m^* \right\}$. The preference information is the vector of weight coefficients $\left\{ w_1, w_2, \ldots, w_m \right\}$. For a multiple-objective optimization problem, the standard goal attainment formulation is given by:

Minimize $\gamma$

where $\gamma \in \mathbb{R}$

subject to:

$f_i \sum w_i \gamma \leq f_i^*; \forall i = 1, \ldots, m$
Where the term $w_i \gamma$ introduces an element of slackness so that hard constraints, $f_i \leq f_i^*$ are avoid. The weighting vector, $w$, enables the designer to express a measure of the relative tradeoffs between the objectives. For instance, setting the weighting vector $W$ equal to the initial goals indicates that the same percentage under- or overachievement of the goals, $F^*$, is achieved. Also, incorporates hard constraints into the design by setting a particular weighting factor to zero (i.e., $w_i = 0$) is possible using this method.

The goal attainment method provides a convenient intuitive interpretation of the design problem, which are solvable using standard optimization procedures.

A geometrically illustration of the goal attainment method is presented in the Figure 1 for a two dimensional problem, whose equations are given by:

\[
\begin{align*}
&\text{Minimize} \quad \gamma \\
&\text{subject to:} \\
&f_1 \leq w_1 \gamma \leq f_1^* \\
&f_2 \leq w_2 \gamma \leq f_2^* \\
\end{align*}
\]

Figure 1. Goal attainment geometrically two dimensions illustration (From MATLAB User’s Manual)

Specification of the goals, $[f_1^*, f_2^*]$ defines the goal point, “Goal”. The weighting vector $[w_1, w_2]$, defines the direction of search from “Goal” to the feasible objective space. During the optimization $\gamma$ is varied, which changes the size of the feasible region.

The MATLAB software, version 7 from MathWorks was utilized to solve the goal attainment problem using the $fgoalattain$ function. Although the problem to solve in this research is a linear programming approach, the goal attainment method has the advantage that it can be posed as a nonlinear programming problem and solved by a Sequential Quadratic Progamming (SQP) method.

2.3 GOAL PROGRAMMING ALGORITHM DESCRIPTION

Goal programming method can be thought of as an extension or generalization of linear programming to handle multiple, normally conflicting objective measures and where a compromise solution instead of a
single solution is looked for, based on the relative importance of each objective (Deb, 2001; 1995). Each of these measures is given a goal or target value to be achieved. Unwanted deviations from this set of target values are then minimized in an achievement function. This can be a vector or a weighted sum dependent on the goal programming variant used.

Conceptually, the goal programming works as follows:

\[
\text{goal } x \in S; \quad \text{with } S \text{ the feasible search region}
\]

This problem has two possible cases. The first one is when the target value \( t \) is smaller than the optimal objective value \( f^{*} \), meaning that no feasible solution exists to attain the goal exactly. The objective of goal programming is then to find that solution which will minimize the deviation \( d \) between the achievement of the goal and the aspiration target \( t \). In this case the solution is still \( x^{*} \) and the overestimate is \( d = f^{*} - t \).

The second case is when the target \( t \) is larger than the maximum feasible cost \( f_{\text{max}} \), the solution of the goal programming problem is \( x \) which makes the objective value exactly equal to \( t \). Although this solution may not be the optimal solution of the constrained \( f(x) \), this solution is the outcome of the above goal program (Deb, 2001).

Although the above conceptual example is for a single function, the concept in a multi-objective optimization problem can be applied in the same way.

### 2.4 Weighted Goal Programming

To solve a multi-objective optimization problem using this method, a composite objective function with deviations from each of \( M \) objectives is used. Mathematically, we have:

\[
\text{Minimize } \sum_{j=1}^{M} \alpha_{j}\rho_{j} + \beta_{j}\eta_{j}
\]

Subject to \( f_{j} \rho_{j} + \eta_{j} = t_{j}, \quad j = 1,2,\ldots,M \)

\( x \in S \)

\( \eta_{j}, \rho_{j} \geq 0, \quad j = 1,2,\ldots,M \)

Where the \( \alpha_{j} \) and \( \beta_{j} \) are weighting factors for positive and negative deviations of the \( j \)-th objective. For less-than-equal-to type goals, the parameter \( \beta_{j} \) is zero and for the greater-than-equal-to type goals, the \( \alpha_{j} \) is zero.

In the Goal Programming method two classes of restrictions are considered; the system constraints and the goal constraints.

### 2.5 Scenarios Description
A total of six possible scenarios are detailed for each sub watershed in the study area, for a total of 18 mathematical models to evaluate. Scenarios were codified as Scenario 1, 2 and 3 for those with an environmental goal based on the proposed nutrients water quality regulation submitted by the University of Puerto Rico using the National Nutrient Criteria Program guidelines from the U.S. Environmental Protection Agency (Martínez et al., 2006). Scenarios 11 to 13 are for those with an environmental goal based on the actual regulation imposed by the Puerto Rico Water Quality Board (PREQB, 2003).

Fundamentals for the first group scenarios (Scenarios 1 to 3) are the same for the second one (Scenarios 11 to 13), with the difference focused in the water quality target depending on the regulation used.

Results from the optimization model show the suggested ranges in land use changes by sub-watershed at the end of the planning year 2025. These results were implemented according to a predetermined creation in a Geographical Information System model (GIS model) presented in a separate document in this Conference by the authors. Following is a description of the results obtained by scenarios considered in the study:

Scenario 1; Priority: Urban and Agriculture land use growth

This scenario combines the Urban or built-up development as well as Agricultural growth giving the same priority for both of them. Forest conservation is a priority in all the scenarios and no trade-off with this land use is permissible. Forest land use growth is set-up in the model to oscillate between 1 to 3% according to the actual Puerto Rico state policies in incrementing those areas.

All created scenarios are hypothetical but based on future possible projections. The main idea is to evaluate the behavior in the trade-off between the existent land use in the area according to priorities in the growth of the main sectors. Pasture is considered a part of the agricultural activity, meaning that some of the possible growth in agriculture will be assigned to Pasture land use. Rangeland and Barrenland are the land use available areas to be converted in Agriculture or Urban.

Scenario 2; Priority: Urban land use growth

Urban land use growth is the priority in this scenario, supposing that agriculture can grow but at low rates with respect to urban. In the construction of hypothetical scenarios, the main idea is to determine multiple possible growth patterns in the area in compliance of water quality criteria in rivers and consequently reservoirs. Scenario 2 gives the priority to urban development to find the maximum possible increment in this landuse.

Additionally, Scenario 2 is formulated as a less ambitious scenario in terms of agriculture growth. It may reflect the actual situation in the agriculture condition of the region, where this economic activity does not have too many incentives.

Scenario 3; Priority: Agriculture land use growth

Agriculture activity in the study region needs to be activated to secure food security for the future of the country. Based on actual trends, researchers of the world foresee this topic as a priority in the countries of the world. Alimentary security will be a hot topic in the next 25 years, the time horizon of this study
and is the reason to evaluate how much the agriculture land use can grow in the future according to the existent conditions in the study area.

In this scenario, agriculture growth is the main priority and urban areas are set up to grow too but in at a much lower rate that those in Scenario 2. The results from these scenarios will allow determining the maximum possible growth in agricultural activities for the next 25 years in the region.

### 2.6 Water Quality Targets

Two water quality standards were considered in the analysis: a) the existing water quality standards by the Puerto Rico Environmental Quality Board (PREQB, 2003) and the USEPA, and b) a proposed new water quality standard developed by the University of Puerto Rico for nutrient standards (Martínez et al., 2006).

<table>
<thead>
<tr>
<th>Station#-Subwatershed</th>
<th>Total Nitrogen* (Kg/year)</th>
<th>Total Phosphorus** (Kg/year)</th>
<th>Total Sediments+ (Kg/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual criteria (1)</td>
<td>Proposed Criteria (2)</td>
<td>Actual criteria (3)</td>
</tr>
<tr>
<td>50025000-RGA</td>
<td>3,932,983</td>
<td>166,652</td>
<td>6,667</td>
</tr>
<tr>
<td>50026025-Caonillas</td>
<td>3,820,967</td>
<td>91,411</td>
<td>3,655</td>
</tr>
<tr>
<td>50026025-Limón</td>
<td>4,659,919</td>
<td>66,665</td>
<td>2,667</td>
</tr>
</tbody>
</table>

(1) Standard for Total Ammonia (PREQB, 2003)
(2) Proposed standard for Total Nitrogen (Martínez et al., 2006)
(3) Standard for Total Phosphorus (PREQB, 2003)
(4) Proposed standard for Total Phosphorus (Martínez et al., 2006)

### 2.7 Decision Variables

Five categories of land uses corresponding to the 99% of total land use in the watershed were used as the decision variables in the multi-objective optimization analysis. The five decision variables are:

\[
X_1 = \text{The optimal area reserved for forest conservation.} \\
X_2 = \text{The optimal area allowed for agricultural development.} \\
X_3 = \text{The optimal area assigned for urban development.} \\
X_4 = \text{The optimal area reserved for pastures growth.} \\
X_5 = \text{The optimal area reserved for range land.} \\
\]
2.8 OBJECTIVE FUNCTIONS

Water quality achievement is the highest priority in this optimization analysis. It implies that water quality standards and respective maximum permissible loads need to be considered as a constraint of the system as well as the objective functions to be minimized in the system. Three objectives functions related to water quality impacts and total discharges of Nitrogen (TN), Phosphorus (TP) and Sediment yield from soil erosion (TS) were proposed.

The three objective functions are:

\[ Z_1 = \text{The objective function of total phosphorus discharge (TP)}; \]
\[ Z_2 = \text{The objective function of total nitrogen discharge (TN)}; \]
\[ Z_3 = \text{The objective function of total discharge of sediment yield, (TS)}. \]

2.9 CONSTRAINTS

Two different types of constraints were incorporated in the mathematical model. The first type consists of system constraints regarding to the actual land use and minimal areas needed for optimal land management and development. The second type are goal constraints, they provide a measure of the assimilative capacity to different pollution impacts (maximum permissible loads) reaching the water body.

3 RESULTS

For the sake of space only results from Scenario 1 is presented in detail in this section, additional scenarios are presented in the full poster presentation.

<table>
<thead>
<tr>
<th>Sub-watershed</th>
<th>Land Use</th>
<th>2005 Actual Value (Ha)</th>
<th>2025 Lower Bound (Ha)</th>
<th>2025 Upper Bound (Ha)</th>
<th>Interval (Ha)</th>
<th>Mid. Value (Ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGA</td>
<td>Forest</td>
<td>14,653.1</td>
<td>14,689.4</td>
<td>14,699.2</td>
<td>9.8</td>
<td>14,694.3</td>
</tr>
<tr>
<td></td>
<td>Agriculture</td>
<td>1,286.3</td>
<td>1,363.5</td>
<td>1,416.6</td>
<td>53.1</td>
<td>1,390.1</td>
</tr>
<tr>
<td></td>
<td>Urban</td>
<td>883.7</td>
<td>948.8</td>
<td>978.4</td>
<td>29.6</td>
<td>963.6</td>
</tr>
<tr>
<td></td>
<td>Pasture</td>
<td>11.7</td>
<td>35.8</td>
<td>78.5</td>
<td>42.7</td>
<td>57.2</td>
</tr>
<tr>
<td></td>
<td>Rangeland</td>
<td>1,713.3</td>
<td>1,452.4</td>
<td>1,482.7</td>
<td>30.3</td>
<td>1,467.6</td>
</tr>
<tr>
<td>CAONILLAS</td>
<td>Forest</td>
<td>8,155.7</td>
<td>8,159.6</td>
<td>8,160.1</td>
<td>0.5</td>
<td>8,159.9</td>
</tr>
<tr>
<td></td>
<td>Agriculture</td>
<td>643</td>
<td>710.8</td>
<td>733.1</td>
<td>22.3</td>
<td>721.9</td>
</tr>
<tr>
<td></td>
<td>Urban</td>
<td>283.7</td>
<td>409.1</td>
<td>414.8</td>
<td>5.7</td>
<td>411.9</td>
</tr>
</tbody>
</table>

Table 2: Land uses optimization values summarize (Scenario 1)
Pasture  |  180.9 |  197.3 |  198.3 |  1.0  |  197.9  \\
Rangeland |  2,970.9 |  2,762.5 |  2,792.2 |  29.7 |  2777.4  \\

LIMON

Forest    |  7,627.0 |  7,676.7 |  7,682.5 |  5.8  |  7,679.6  \\
Agriculture |  694.7   |   728    |   763.4   |  35.4 |   745.7    \\
Urban      |   165.2  |   174.8  |   187.9   |  13.1 |  181.35   \\
Pasture    |   102.3  |   104.7  |   110.9   |   6.2 |  107.8    \\
Rangeland  |   784.9  |   654.6  |   676.3   |  21.7 |  665.45   

**Table 3: Land use probable conversion based on mean optimization modeling output. Scenario 1 (Forest conservation + agriculture and urban growth)**

<table>
<thead>
<tr>
<th>Land use</th>
<th>Sub-watershed land conversion (Ha)</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RGA</td>
<td>Caonillas</td>
</tr>
<tr>
<td>Forest</td>
<td>38.3 (0.26%)</td>
<td>4.1 (0.05%)</td>
</tr>
<tr>
<td>Agriculture</td>
<td>104.0 (8.09%)</td>
<td>78.9 (12.28%)</td>
</tr>
<tr>
<td>Urban</td>
<td>79.6 (9.00%)</td>
<td>128.2 (45.20%)</td>
</tr>
<tr>
<td>Pasture</td>
<td>45.4 (388.3%)</td>
<td>16.9 (9.33%)</td>
</tr>
<tr>
<td>Rangeland</td>
<td>-245.4 (14.33%)</td>
<td>-193.6 (6.52%)</td>
</tr>
<tr>
<td>Barrenland</td>
<td>-24.5</td>
<td>-34.1</td>
</tr>
<tr>
<td>Water</td>
<td>0.0 (0%)</td>
<td>0.0 (0%)</td>
</tr>
</tbody>
</table>

*Negative values means a decrease in the land use tradeoff.

**4. CONCLUSIONS**

A Multi-objective Linear Programming (MOLP) approach was incorporated in this research in order to be used as a mathematical tool for the evaluation of a series of hypothetical scenarios searching for the optimal land use combination for the year 2025, the planning year. Scenarios formulation evaluated hypothetic cases to see the behavior of the main economic activities under possible combinations and get an idea about the potential growth of those strongest activities in the area like the agriculture and urban.

A solid social and economic research about the historical tendencies and data of the municipalities inside the RGA watershed complemented with interviews with experts in the land use planning area, agriculture economic activity and local, state and federal agencies were taken into account in the models formulation to come up with possible future conditions in the area.

The MOLP methodology uses the results from a ten years water quality simulation model to incorporate the nutrients and sediments land use export coefficients summarized in an interval and introducing the inherent uncertainty in this type of nature process. MOLP methodology incorporates uncertainty associated to the model decision variables giving from the export coefficients associated to each landuse
type analyzed in this research. This consideration produces more realistic results compared with a deterministic formulation where unique solution is available instead of multiple optimal possible combinations.

The wildcards land uses including the rangeland and barren land and defined as lower profitable land uses, tends to decrease in a major proportion for Scenarios 11 to 13 with respect to scenarios 1 to 3. Balance in the system is the reason of a major wildcard trade off due to the potential growth of more rentable land uses (urban and agriculture) obtained in Scenarios 11 to 13.

The Forest areas in the MOLP results tend to be incremented in a percent around 1% as maximum. No decrease in this land use is allowed.

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REFERENCES


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