COASTAL RESOURCE MANAGEMENT: A SYSTEMS APPROACH

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ABSTRACT: Managing coastal resources requires systems approach to provide scientific knowledge and information to support the decision-making process aimed at achieving the priority development goals. Due to the fast degradation of the limited resources available in coastal communities and several allocation resource management problems, it is imperative that decision makers have a sound basis or reference point. This can be attained through optimal land and water use allocation in which maximization of economic value of land and water resources, land and water suitability, adaptive capacity of people and minimization of disaster risk should be carefully studied and analyzed. The present work provides insight in developing decision support system as reference of the policy makers to solve specific decision problems in coastal resource management using multi-goal linear programming model formulation and optimality assessment. The methods presented are general and can be adopted and in managing coastal ecosystems elsewhere.

1. INTRODUCTION

Philippines is endowed with rich coastal ecosystems. They provide a wide range of valuable services to human society (Chung et al. 2015). However, like all other ecosystems, they are vulnerable to degradation because of unplanned and uncontrolled use of coastal resources such as fisheries, coral reefs, seagrasses and mangroves that provide both direct and indirect benefits in coastal communities (DENR, 2001). Coastal resource management is needed to protect and maintain its huge ecological services and economic resources to sustainably provide food, medicine, tourism attraction, hazard protection and among others.

The absence of coastal resources valuation is one of the major reasons why coastal resources are being threatened. The economic values of the coastal ecosystem services are often underestimated in cost benefit analyses for conservation versus other alternative land uses such as shoreline constructions, ports and other poorly planned engineering works. Thus, proper accounting and valuation of the multiple services provided by coastal ecosystems is important for a more efficient choice in policy making decisions. Accurate estimates for the economic value of ecosystems are also needed to justify its sustainable development and maintenance.

Coastal resource management can be attained through optimal land use and water use allocation in which maximization of economic value of land and water resources, land and water suitability, adaptive capacity of people and minimization of disaster risk are needed. Land resources provide more stable support for the economic development of most countries which is the reason why optimal allocation of land is vitally important. Optimal allocation of water resources is equally essential (Tang & Wang, 2018). Moreover, land suitability analysis is done to recommend more suitable crops to be produced in specific areas in which soil texture, organic matter content, soil depth, slope and drainage are taken into consideration. In this way, the experts can detect the environmental limit in sustainable land use planning together with the minimized disaster risk that can achieve safer optimal land use allocation (Bandyopadhyay et al., 2009). Although adaptive capacity is uniquely an under-researched topic, it is as essential as the other goals because it is an element of long-term adaptation to climate change wherein people have the capability to anticipate or deal with climate and development pressure while still considering the maintenance and improvement of their wellbeing. In this case, maximizing adaptive capacity will highly ensure a more effective optimization of land use allocation because it considers the community and its environmental resources as a whole (Siders, 2019). Through the aforementioned management of coastal resources, humans can see to it that there would be prevention with further damage and overexploitation of the coastal ecosystems along with their natural capability to produce at the extent of causing permanent damage to the system and their products (White & Cruz-Trinidad, 1998).

In an effort to provide information to support the decision-making process in coastal resource management, a systems approach is developed to achieve the priority development goals of coastal areas. With the aid of Gurobi®, a linear programming software, optimum land and water use allocation can be provided based on the model formulated. Multiple Goal Linear Programming (MGLP) is used when there are indeed multiple conflicting objectives in land use planning such as economic development (gaining the most profit), social development (residential areas with lowest disaster risk), and environmental management (climate change adaptation) among others. The results of the MGLP are the spatial decision-support system (SDDS) that can be the basis of policy-makers in terms of land use planning translated into zoning ordinance.

2. SYSTEMS APPROACH

Major steps in the formulation of a decision support system for coastal resource management are presented in Figure 1.

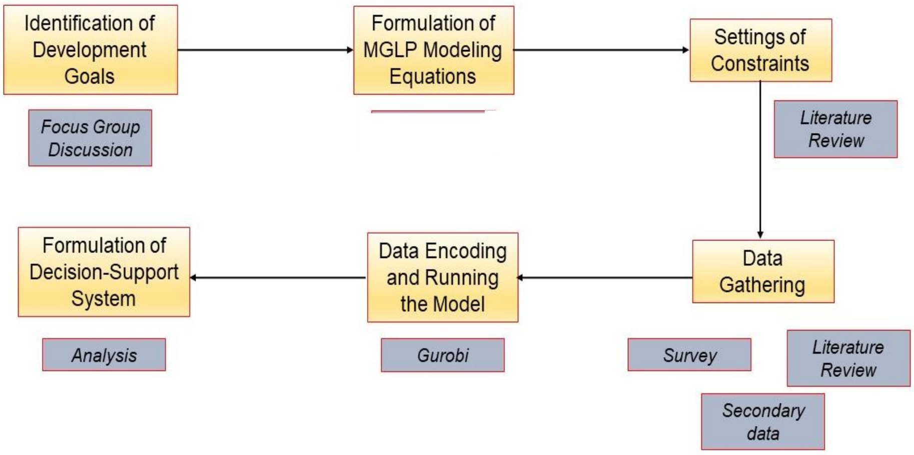

Figure 1. Research procedure of the study

2.1 Identification of Development Goals

The procedure starts with the identification of the development goals of a specific coastal area. The participation and cooperation of the policy makers are important in the research approach thus, the initial objective is to get their consensus regarding their priorities in the management of coastal resources. The agreed development goals will become the basis of the objective functions. Several development goals are listed for illustrative purposes which can be adopted in different sequence depending on the priority of the policy makers.

List of development goals may include: 1) disaster risk reduction, 2) provision of livelihood, 3) coastal resources conservation and protection, and 4) climate change adaptation.

2.2 Formulation of MGLP Modeling Equations

The priority development goals identified will be translated into four (4) objective functions for land use allocation and three (3) for water use allocation. Mathematical equations for land and water use allocation are formulated based on the objective functions.

For land use allocation, the decision variable, a binary variable (1 and 0), is the land use (land_use) that Gurobi will assign in each grid (g). Land use options (u) of each municipality may include six (6) crops and built-up use.

In minimizing disaster risk (Eq. 1), summation of the binary variable of each grid assigned to built-up use ($\mathrm{land\_use}_{g,b}$) multiplied with the average disaster risk score of each grid ($\mathrm{disaster\_risk}_{g}$), is obtained.

$$Minimize\ disaster\ risk = \sum_{g=1}^{ng} \mathrm{land\_use}_{g,b} * \mathrm{disaster\_risk}_{g} \qquad \text{Eq. 1}$$

Maximizing land suitability (Eq. 2) is solved by obtaining the summation of the binary variable of each grid assigned to land use options ($\mathrm{land\_use}_{g,u}$) multiplied by the suitability rating of each grid of that land use option assigned ($\mathrm{suitability}_{g,u}$).

$$Maximize\ suitability = \sum_{g=1}^{ng} \mathrm{land\_use}_{g,u} * \mathrm{suitability}_{g,u} \qquad \text{Eq. 2}$$

Maximizing the economic value (Eq. 3) is solved by getting the summation of the binary variable of each grid assigned to land use options ($\mathrm{land\_use}_{g,u}$) multiplied with the total economic value of each grid of the land use option assigned ($\mathrm{econ\_value}_{gu}$).

$$Maximize\ total\ economic\ value = \sum_{g=1}^{ng} \mathrm{land\_use}_{g,u} * \mathrm{econ\_value}_{gu} \qquad \text{Eq. 3}$$

To solve the objective function of maximizing the adaptive capacity (Eq. 4), the summation of binary variable of each grid assigned to land use options ($\mathrm{land\_use}_{g,u}$) multiplied by the adaptive capacity of the people living in that particular area (ac_g)and the flood index score of each land use ($\mathrm{fac}_{g,u}$), are considered.

$$Maximize\ adaptive\ capacity = \sum_{g=1}^{ng} \mathrm{land\_use}_{g,u} * \mathrm{ac}_g * \mathrm{fac}_{g,u} \qquad \text{Eq. 4}$$

For water use allocation, the decision variable, a binary variable (1 and 0), is the water use (water_use) that Gurobi will assign in each grid. There may be six (6) water use options for a study are, namely, mangrove forest, coral reef, seagrass bed, fish cage, marine protected area and municipal fishing area.

To minimize disaster risk, mangrove use is maximized (Eq. 5). Summation of the binary variable of each grid assigned to mangrove ($\mathrm{water\_use}_{g,m}$), multiplied with the storm surge risk score of each gird ($\mathrm{disaster\_risk}_g$) is obtained.

$$Maximize\ mangrove\ use = \sum_{g=1}^{ng} \mathrm{water\_use}_{g,m} * \mathrm{disaster\_risk}_g \qquad \text{Eq. 5}$$

Maximizing water suitability (Eq. 6) can be computed by getting the summation of the binary variable of each grid assigned to water use options ($\mathrm{water\_use}_{g,u}$) multiplied by the suitability rating of each grid of that water use option assigned ($\mathrm{suitability}_{g,u}$).

$$Maximize\ water\ suitability = \sum_{g=1}^{ng} \mathrm{water\_use}_{g,u} * \mathrm{suitability}_{g,u} \qquad \text{Eq. 6}$$

For the third objective function, maximizing economic value (Eq. 7) is calculated by getting the summation of the binary variable of each grid assigned to water use options ($\mathrm{water\_use}_{g,u}$) multiplied by the total economic value of each grid ($\mathrm{econ\_value}_{g,u}$).

$$Maximize\ total\ economic\ value = \sum_{g=1}^{ng} \mathrm{water\_use}_{g,u} * \mathrm{econ\_value}_{g,u} \qquad \text{Eq. 7}$$

2.3 Setting of Constraints

For the model to run or provide feasible solution, constraints for both land use and water use allocation will be set. Constraints are restrictions on the decision variables. It limits the value of the decision variables, so that it cannot go above (setting a maximum or <=) or below (setting a minimum or >=) a certain value of the variable.

2.3.1 Land use allocation: There are five (5) initial constraints that will be set for land use allocation.

a. Land area requirement (Eq. 8) –The first constraint ensures that land use that will be assigned by Gurobi will not go beyond the total available land or the agricultural land. Area of total land managed (i.e., remaining agricultural land) can be computed using GIS.

$$\sum_{\mathrm{g}=1}^{\mathrm{ng}} \mathrm{land\_use}_{\mathrm{g,u}} * \mathrm{size}_{\mathrm{g}} \leq \mathrm{total\_land} \qquad \text{Eq. 8}$$

b. Minimum residential area requirement (Eq. 9) – This ensures that the area that will be assigned for built-up use would not go below the minimum residential area requirement. This can be obtained by determining the projected housing demand by the additional population and the projected housing need from those with dilapidated houses.

$$\sum_{\mathrm{g}=1}^{\mathrm{ng}} \mathrm{land\_use}_{\mathrm{g,7}} * \mathrm{size}_{\mathrm{g}} \geq \mathrm{min\_res} \qquad \text{Eq. 9}$$

c. Minimum production requirement per crop (Eq. 10) – This ensures that the crop production will not go below the product demand or requirement. The demand for each crop can be determined using the per capita consumption multiplied by the population of the study site. Average production of the different crops to be evaluated can be drawn from literature.

$$\sum_{\mathrm{g}=1}^{\mathrm{ng}} \mathrm{land\_use}_{\mathrm{g,u}} * \mathrm{produce}_{\mathrm{u}} \geq \mathrm{demand}_{\mathrm{u}} \qquad \text{Eq. 10}$$

d. Water availability (Eq. 11) – This ensures that the assigned land use multiplied by their respective water requirement will not go beyond the total water supply of the stud area. The water supply can be estimated by getting the sum of the amount of annual rainfall and volume of water coming from irrigation.

$$\sum_{\mathrm{g}=1}^{\mathrm{ng}} \mathrm{land\_use}_{\mathrm{g,u}} * \mathrm{water}_{\mathrm{u}} \leq \mathrm{total\ water}_{\mathrm{u}} \qquad \text{Eq. 11}$$

e. One assignment, one grid (Eq. 12) – This is to ensure that there is only one land use assigned to one grid.

$$\sum_{\mathrm{g}=1}^{\mathrm{ng}} \mathrm{land\_use}_{\mathrm{g,u}} \quad == 1 \qquad \text{Eq. 12}$$

2.3.2 Water use allocation: There are four initial constraints that will be set for water use allocation.

a. Rehabilitation/conservation cost of mangrove forest, coral reef and seagrass bed and establishment of MPA (Eq. 13) – This ensures that the rehabilitation or establishment cost of the water use that will be assigned by Gurobi will not go beyond the total rehabilitation fund allotted by the local government unit. Rehabilitation or establishment costs can be obtained from literature and management plan of the selected coastal region.

$$\sum_{g=1}^{ng} \mathrm{water\_use}_{g,u} * \mathrm{cost\_rehab}_{u} \leq \mathrm{rehab\_fund} \qquad \text{Eq. 13}$$

b. One assignment, one grid (Eq. 14) – This is to ensure that there is only one land use assigned to one grid.

$$\sum_{g=1}^{ng} \mathrm{water\_use}_{g,u} \quad == 1 \qquad \text{Eq. 14}$$

c. There should be at least one grid for seagrass bed, coral reef and mangrove forest (Eq. 15). This will be set to ensure that there would be a grid assigned to the water use with ecological and economic importance.

$$\sum_{g=1}^{ng} \mathrm{water\_use}_{g,u} \quad \geq 1 \qquad \text{Eq. 15}$$

d. Additional MPA needed (including coral reef and seagrass bed) (Eq. 16) - This is to ensure that the part of the municipal water is allocated to MPA.

$$\sum_{g=1}^{ng} \mathrm{size}_{g} * (\mathrm{water\_use}_{g,5} + \mathrm{water\_use}_{g,3} + \mathrm{water\_use}_{g,2}) \quad \geq \mathrm{min\_mpa} \qquad \text{Eq. 16}$$

e. Minimum fish production requirement (Eq. 17) – This ensures that the area allotted for fish cage will have a production that will not go below the fish consumption requirement. The demand for fish can be determined using the per capita consumption of fish multiplied with the population of study site.

$$\sum_{g=1}^{ng} \mathrm{water\_use}_{g,u} * \mathrm{size}_{g} * \mathrm{fish\_prod} \geq \mathrm{total\_demand} \qquad \text{Eq. 17}$$

f. Maximum area for fish cage (Eq. 18) – This ensures that the water use that will be assigned by Gurobi will not go beyond the maximum allowable area for fish cage. The maximum allowable area for fish cage depends on the analysis of Fisheries Office or carrying capacity assessment.

$$\sum_{g=1}^{ng} \mathrm{water\_use}_{g,4} * \mathrm{size}_{g} \leq \mathrm{max\_fc} \qquad \text{Eq. 18}$$

2.4 Data Gathering

The following are the necessary primary and secondary data:

Maps needed for the delineation of land and water management units: land administrative boundary, land cover, soil type, slope, municipal water boundary, and area covered by corals, seagrass, mangroves and marine protected area.

For land use allocation: land suitability classification, crop requirements, land qualities, slope, hazard susceptibility, existing land use/land cover, accessibility, total economic value of agricultural land, gross income of farmers, assessed value of land, total economic value of built-up land, gross income of commercial establishments, assessed value of residential and commercial lands, disaster risk score, and adaptive capacity index score.

For the constraints on land use allocation: minimum residential area requirement, population and growth rate, housing condition, minimum production requirement per crop, per capita consumption of the major crops, average crop production, water availability, water requirement of crops and the population, number of commercial establishments, and water supply.

For water use allocation: water suitability classification, bathymetry, temperature, nitrite, turbidity, salinity, phosphate, sediment, proximity to the existing coral, current seagrass distribution, proximity to natural seagrass bed, total suspended solids (TSS), type of shoreline, tidal rate, relative naturalness, representativeness, biodiversity, vulnerability, fisheries value, and total economic value of coastal resources.

For constraints on water use allocation: rehabilitation or establishment cost of mangrove forest, coral reef, seagrass bed and MPA, rehabilitation fund, minimum area for MPA, minimum fish production requirement, production of fish cages, total demand for fish, and maximum allowable area for fish cage.

2.4.1 Land use allocation

Delineation of land management units is done by overlaying the soil type, slope, land cover and administrative boundary maps using geographic information system (GIS). Forest, built-up and riverbeds are eliminated from total land area, leaving agricultural area as the land to be managed. The land management unit generated is further divided into one- hectare grid.

Land suitability classification using the limitation method regarding number and intensity of limitations devised by Food and Agricultural Organization (FAO) is adopted. Crops evaluated are the major crops of the study area.

Crop requirements can be obtained from Land Evaluation authored by Sys, et al. Land characteristics are evaluated against the requirements of the crops. This includes slope (t), flooding (w), drainage (h), coarse fragments or surface stoniness (s), soil depth (d) and fertility limitations (f). Ranges of classes used in land suitability are highly suitable (S1), moderately suitable (S2), marginally suitable (S3), currently not suitable (N1), and permanently not suitable (N2) (Sys, C.; Van Ranst, E.; Debaveye, 1993). These are translated into land suitability index scores (5, 4, 3, 2 and 1, respectively) assigned to each grid as inputs to MGLP.

Factors to be considered in the land suitability for built-up use include slope, existing land use, accessibility, and hazard susceptibility. To provide weights of the different factors in a pairwise manner, outputs from the experts will be solicited and their answers will be subjected to Analytical Hierarchy Process (AHP) devised by Saaty.

Disaster risk scores can be obtained from disaster risk assessments. The scores can be computed by multiplying hazard scores with vulnerability scores. Hazards such as flood, storm surge, tsunami, and landslide can be considered. Vulnerability, on the other hand, is a function of sensitivity and adaptive capacity. Average disaster risk score of the study area in relation to the four hazards is computed and encoded in the database.

Adaptive capacity (AC) score of the agricultural and built-up sectors on flooding can be obtained from vulnerability assessment. The AC score is multiplied with the flooding tolerance index score of the land uses or the crops and the built-up area.

Total economic values (TEV) of the different land uses can be drawn from primary and secondary data. Faming household survey, using structured questionnaire is conducted in the selected study area to determine the gross income of farmers. The assessed values of residential and commercial lands can be gathered from the Assessor's Office of the study area, whereas, the income of commercial establishments can be obtained from the Business Permit and Licensing Office.

2.4.2 Water use allocation

The disaster risk score in relation to storm surge is used in determining the disaster risk value of the first three grids of the municipal water from the shoreline. The data is obtained from disaster risk assessment in the study area.

Parameters of suitability for mangrove forestation or rehabilitation are tidal rate, bathymetry, and type of shoreline (Suprakto & Arfiati, 2014). Water suitability for coral reef establishment or restoration is based on temperature, salinity, phosphate, bathymetry, sediment, and proximity to existing corals (Guan et al., 2015).

Site suitability criteria as recommended by UNDP/FAO (1989) is used in establishing fish cages. It includes the topographical criteria (depth or bathymetry), physical criteria (temperature and turbidity), and chemical criteria (nitrite). Establishing a marine protected area (MPA) requires ecological, social and economic preparedness of the community. Ecological criteria include the relative naturalness, representativeness, biodiversity, vulnerability, and fisheries value (*c.f.* K. Saputra et al., 2017; Post, 2016). The rest of the municipal water is considered as fishing area of small-scale fisherfolks; thus, the grids are scored automatically with suitability rating of 2.

Weight of factors influencing the water suitability for the different water uses is evaluated employing AHP. Marine science experts are the evaluators. Water uses of the municipal water of the study sites include mangrove forest, coral reef, seagrass bed, fish cage, marine protected area (MPA) and municipal fishing area (MFA). MFA is the area of the municipal water less the area devoted to the first five uses and where small-scale fisherfolks can do fishing

Total economic values (TEVs) of the mangrove forest, coral reefs and seagrass beds are computed through economic valuation. Fish catch in municipal water is drawn from the fishery office of the study site.

2.5 Data Encoding and Running the Model

Data needed for land use allocation of the study site, namely, total economic value of the land uses, disaster risk score of the built-up sector, adaptive capacity on flooding and flooding tolerance index score of the crops and built-up, the land suitability scores of the crops and built-up, and the constraints, are encoded in spreadsheets. In the same manner, data needed for water use allocation, namely, total economic value of water uses, disaster risk score pertaining to storm surge, and the water suitability scores of the water uses, are encoded in spreadsheets.

All equations are written in the Solver Studio interface following the steps: 1) encoding and defining the decision variables; 2) encoding the objective function equations; 3) encoding the constraint equations; 4) entering the command to view the model output; and 5) running the model.

2.6 Formulation of Decision-Support System

Land use and water use allocation options can be developed out of the optimization results of running the model. These options could become the basis for policy makers to arrive at sound decisions regarding the use and management of their coastal resources. The outputs from Gurobi can be presented visually through GIS.

3. CONCLUSION

A multi-goal linear programming model with the aid of Gurobi is a useful as a tool in the formulation of decision-support system for coastal resource management. The allocation is done in a systems approach since both the land and water resources and their total economic values, suitability of the land and water, the disaster risks and adaptive capacity of the residents and farmers on flooding, are considered holistically.

Given the solution discussed in this study, a more realistic representation that can be used for planning and decision making can be provided by optimally allocating land and water use leading to the attainment of managing coastal resources. The optimum allocation of uses ensures that maximum benefits would be obtained from land and water resources.

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