A CONFLICT BETWEEN ENVIRONMENTAL AND ECONOMIC ISSUES IN AN IRRIGATION DISTRICT IN MEXICO

Raquel Salazar, Universidad Autónoma Chapingo, Km 38.5 Carr. México-Texcoco, Chapingo Edo. México, 56230, raquels@correo.chapingo.mx
Ferenc Szidarovszky, Department of Systems and Industrial Engineering, The University of Arizona, Tucson, Arizona 85721-0020, USA, szidar@sie.arizona.edu
Emery Coppola, NOAH LLC, 610 Laurence Road , Laurenceville, New Jersey, 08648 USA emerynoah@comcast.net
Abraham Rojano, Universidad Autónoma Chapingo, Km 38.5 Carr. México-Texcoco, Chapingo Edo. México, 56230, abrojano@correo.chapingo.mx

ABSTRACT

The Alto Rio Lerma Irrigation District is located in Mexico, where economic benefits from agricultural production need to be balanced with associated negative environmental impacts. The short period of rainfall in this area, has produced severe aquifer overdraft. Current agricultural practices of applying high loads of fertilizers and pesticides have contaminated regions of the aquifers. The two primary stakeholders or players, the farmers in the irrigation district and the community, must find an optimal balance between positive economic benefits and negative environmental impacts. Game theory was applied to find the optimal solution between two conflicting objectives among twelve alternative groundwater extraction scenarios.

INTRODUCTION

The Alto Rio Lerma Irrigation District (ARLID) is an agricultural area whose sustainability depends partially upon groundwater withdrawal from three aquifers, with a command crop area of 37, 772 hectares serviced by approximately 2,100 irrigation wells. In the last years, water competition between residential, industrial and agricultural use has increased. The high concentration of active wells in the ARLID has resulted in an annual aquifer overexploitation ratio of between 1.2 to 1.4, where the annual natural replenishment to the groundwater system via precipitation is exceeded by the annual extraction via wells. In addition, the high chemical loading of fertilizers and pesticides has resulted in elevated chemical concentrations in groundwater, which because it also serves as a drinking water source, poses potential risks to human health.

In the last 10 years, the net returns from the main crops in Mexico have declined drastically due to removal of subsidies and price guarantee programs, significantly reducing the short-term economic incentive for farmers to consider environmental problems. As a consequence, decision makers both at the national and local levels have increasingly had to balance the environmental concerns of society at large with the economic benefits of the farmers. This paper describes the application of Game Theory to a special groundwater management problem in the irrigation district, where a two person conflict arises. The economic benefit is the payoff of the first player (i.e. farmer) and the reduction of the potential environmental risk is the payoff of the second player (i.e. community), with groundwater extraction as the decision variable. The purpose of this study is to identify a solution which balances the economical benefit with environmental concerns.

ATTRIBUTES ESTIMATION

Twelve groundwater extraction scenarios were proposed based upon a 10 year groundwater extraction historical record in the ARLID (Alto Rio Lerma Irrigation District) database. For each groundwater extraction scenario, the two conflicting objectives economic and environment were quantified. The economic objective is the net income generated by a linear program, which maximizes the net income of the farmers, subject to water and land constraints, with pumping costs variable for each scenario due to different lift requirements. The environmental attributes include nutrients and pesticides associated with irrigation runoff and percolation, and a measure of groundwater depletion, collectively computed as a weighted sum of nitrates and pesticides in runoff and percolation and aquifer overexploitation, which depend on crop volumes and water usage. To apply conflict resolution methodology, a comprehensive alternative set for the entire interval between the smallest and largest groundwater extraction scenarios was computed using a special spline interpolation.

GAME THEORY METHODS

Method 1: The **non-symmetric Nash solution**

The non-symmetric Nash solution allows us to model the bargaining of parties with different powers.

$$\text{Maximize } (f_1 - d_1)^{w_1}(f_2 - d_2)^{w_2} \quad \textbf{(1)}$$

$$\text{subject to } d_1 \le f_1 \le f_1^*$$

$$f_2 = g(f_1)$$

where w_1 and w_2 are the powers of the two players, or the importance factors of their objectives.

Method 2: The non-symmetric Kalai-Smorodinsky solution

The non-symmetric Kalai-Smorodinsky solution computes the unique intercept between the Pareto frontier and the straight line.

$$\bar{g}(\bar{f_1}) = (w_2 / w_1)\bar{f_1} \quad \textbf{(2)}$$

when the two coordinate directions are the normalized objective functions.

Method 3: The area monotonic solution

The non-symmetric area monotonic solution requires that the ratio of the areas of the two subsets be w_1/w_2. Hence the first coordinate of the solution is the root of the nonlinear equation

$$w_2[\int_{d_1}^{x} g(t)dt - \frac{1}{2}(x-d_1)(g(x)+d_2)] = w_1[\int_{x}^{f_1^*} g(t)dt - (f_1^* - x)d_2 + \frac{1}{2}(x-d_1)(g(x)-d_2)] \quad \textbf{(3)}$$

Method 4: The equal loss solution

The more important payoff is relaxed slower than the other by requiring the ratio of the relaxation speeds be equal to w_2/w_1. Therefore we determine a point $(x, g(x))$ on the Pareto frontier such that

$$(f_1^* - x)w_1 = (f_2^* - g(x))w_2 \quad \textbf{(4)}$$

RESULTS

Figure 1 depicts the net income obtained in the four methods with different weights. In applying Method 4, the net income increases linearly with increasing economic weight, while the remaining methods exhibit weakly non-linear behavior. When economic benefit is considered as the only objective, the optimal groundwater withdrawal is at its maximum level. At the other extreme, when only environment is considered, the optimal groundwater scenario is to extract the minimum volume of groundwater via the irrigation wells.

Among the twelve original scenarios considered, the seventh groundwater extracted scenario is the closest to these optimal results, with a total annual groundwater extraction 367,000 m^3.

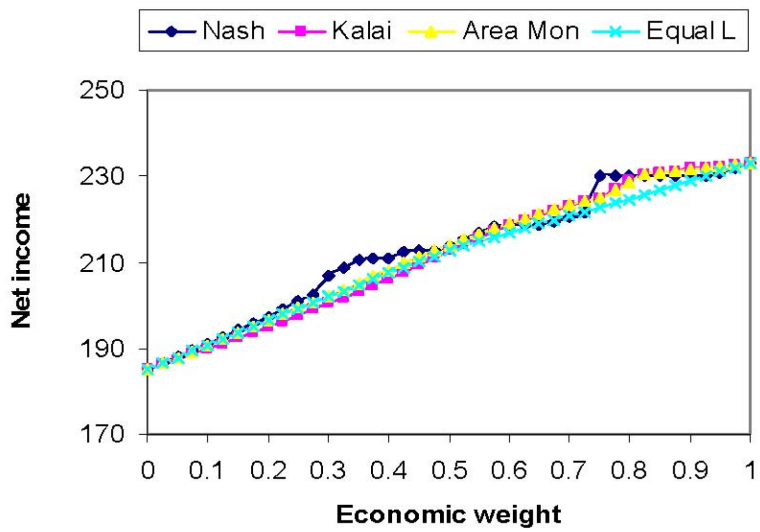

Figure 1. Economic payoff for the four methods with different weight selections.

CONCLUSIONS

This study illustrates how Game Theory can be used to obtain tradeoffs between conflicting objectives in a straightforward and understandable manner that facilitates an objective assessment of the different alternatives from the different points of views of the various stakeholders and/or decision makers. It is also shown that the optimal decision depends on the relative importance weights assigned to the conflicting objectives. In this study, when environmental impact and economic benefit objectives are assigned equal weight or importance, the best scenario is to extract 367-371 million cubic meters of groundwater each year for irrigation. The methodology described and applied in this paper can be successfully applied in many other natural resources management problems where stakeholders with conflicting interests are present.