A STEP Method based multiple objective methodology for irrigation water management to model preferences and tradeoffs

Xevi, E. [1,3] and S. Khan [1,2,3]

[1] CSIRO Land and Water, Griffith, NSW
[2] Charles Sturt University , Wagga Wagga , NSW
[3]Cooperative Research Centre for Irrigation Futures

Email: emmanuel.xevi@csiro.au

Keywords: *Spatial fields, similarity, error, tolerance, comparison*

EXTENDED ABSTRACT

Management decisions relating to river basins are difficult due to the complex interaction of bio-physical, economic and social variables. Moreover, conflicting objectives of different stakeholders have to be considered. Lack of adequate information to determine water allocations, environmental flow requirements and the increasing intensity of cropping systems require a better seasonal distribution of water to satisfy consumptive and in-stream environmental demands. Water demand management that considers system constraints on water conveyance and losses in addition to environment requirements will result in optimum productivity of irrigation areas and better management of river flows. Many decision support systems in agricultural enterprises use conventional linear programming approach to optimize a single objective function such as total gross margin. However, as agricultural systems become more complex, multiple objectives that are in conflict with each other need to be addressed. Mathematical programming techniques are required to formulate the problem and find a compromise solution. A methodology based on the techniques of STEM (Step Method) is provided that allows for the progressive articulation of preferences. This is an iterative procedure that narrows the region on the "efficiency frontier" in which the final compromise solution is found. The procedure involves iterations where preferences are based on the objective space of previous iterations. The decision making process is entirely in the objective space and results are presented in the form of graphs and tables of objective values and utility values. A utility function is used to select the best objective function at each iteration and can take various forms (linear, convex or concave curves). The choice of the utility function is subjective and there is scope for investigating various utility functions. We have adopted a linear utility function in this study. The technique is applied to a hypothetical nodal network shown in Figure 1. For the purpose of this paper, the irrigated area is divided into eight regions with a total irrigable land of 121,808 ha and a potential for growing fourteen crops (rice, wheat, oats, barley, maize, canola, soybean, winter pasture, summer pasture, lucerne, vines, summer vegetables, winter vegetables, citrus and stone fruit). In the current analysis groundwater pumping under the irrigable area is permitted to satisfy crop water demand if surface water supplies are not sufficient.

Therefore the model has the potential to develop conjunctive water management options for achieving a better demand pattern from the surface water. The decision maker participates fully in the process by stipulating her preferences and accepting a compromise solution.

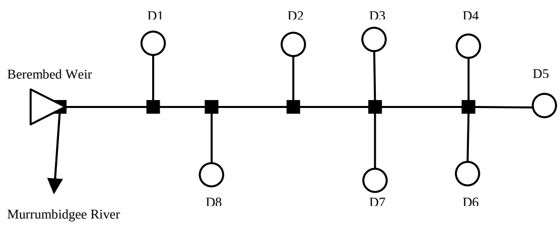

Figure 1: Conceptual nodal network representation

1. INTRODUCTION

As the world's natural resources dwindles, competition for them increases at a rapid pace. In the case for water resources, competition stems from farm level to regional and even national levels often with conflicting goals and objectives. Sustainable irrigation management remains a daunting task (Khan et al. 2006). Irrigation induced waterlogging and salinity reduce agricultural production and impose other economic, social, and the environmental costs (see Houk et al. 2005; Wichelns 2002; Ragan et al. 2000; Wichelns 1999; Hussain et al. 2004). The costs are often not confined to a paddock or private property but spread over a wider scale. There can be a range of off-farm impacts including damages to roads and infrastructure, loss of aesthetic values and reduced biodiversity etc (see Characklis et al. 2005). Other impacts include displacement of labour, out migration, income disparity, and overall reduction in food output. These off-site costs or externalities have important policy implications regarding land and water resources management and how tax dollars are deployed to mitigate salinity and create social benefits for all.

Many decision support systems in agricultural enterprises use conventional linear programming approach to optimize a single objective function such as total gross margin. However, as agricultural systems become more complex, multiple objectives that are in conflict with each other need to be addressed. Irrigation demand management that considers surface and ground water constraints on water conveyance and losses in addition to environment requirements will result in optimum productivity of irrigation areas and better management of river flows. Consequently multi-criteria decision making techniques (MCDM) are necessary to adequately address these complexities. A multi-criteria approach has been used extensively to solve diverse decision problems including risk assessment in agricultural systems (Berbel, 1993). Furthermore, Tecle, (1998) used Compromise Programming (CP) to develop a multi-objective decision support system for analysing multi-resource forest management problem. A method known as the STEM (Step Method) described in Alkan and Shamir (1980) and due to Benayoun et al. (1971) are known as the generating methods where single objective optimisations are constructed and points are generated on the non-inferior set and one of these points is selected as a compromise solution. Using this method the concept of optimal solution in single objective problems that is generally unique is replaced by the concept of nondominated solutions (i.e. feasible solutions for which no improvement in any objective function is possible without sacrificing at least one of the other objective functions).

The multi-objective problem that this model addresses comprise three objective functions: maximizing net returns (NR), minimizing variable cost (VC) and minimizing total supplementary groundwater pumping requirements to meet crop demand from the irrigated areas. The management options to achieve the above objectives consist of selection of an appropriate mix of crops, optimum level of groundwater pumping and appropriate allocation of water for irrigation and environment. Constraints imposed on the system are:

- continuity
- total farm area
- monthly water allocations
- monthly environmental flow requirements
- monthly groundwater pumping

In addition, water allocation rules and pumping targets for each month are constraints imposed on the system.

Input variables required consist of:

- monthly rainfall
- monthly crop water requirements
- crop growth duration
- crop factors
- yield, price and variable cost of crops

In previous work (Xevi and Khan 2003, Xevi and Khan (2005)), we attempted to find solutions to the multiple objective problems using goal programming with weights attached to the objective functions. In this paper we describe a method (STEM) that seeks a compromise solution to multiple objective problems that includes bio-economic objectives with the optimum use of water resources under conflicting demands. Unlike other methods used to solve multi-objective problems, STEM is interactive and involves the decision maker closely. While other methods tend to find solutions at the extreme points of the feasible region, STEM finds non-extreme point efficient solutions by exploring the entire feasible region. A compromise solution acceptable to the decision maker can be found in this interactive method. The method was applied to a conceptual nodal network representation of part of the Murrumbidgee irrigation area in Australia.

Further details about the data used in the model can be found in Xevi and Khan (2003), Xevi and Khan (2005).

2. METHOD AND THEORY

In general, multiple objective problems can be formulated with the following equation (see Alkan and Shamir, 1980)

$$Max\,\underline{f}(x) = [\,f_1(\underline{x}) = \underline{c}_1\,\underline{x};\ ......;\ f_p(\underline{x}) = \underline{c}_p\,\underline{x}]$$
$$\text{subject to } \underline{A}\underline{x} \le b \text{ and } \underline{x} \ge \underline{0} \qquad (1)$$

where $\underline{x}$ is an n-dimensional vector of decision variables, $\underline{A}$ is matrix of technology variables, $\underline{b}$ is a vector of forcing variables and $\underline{f}$ is a vector of p-dimensional objective functions and and $\underline{c}$ is a vector of coefficients.

Taking X as the feasible region in the decision space for equation 1 and M_k as the maximum value attainable by solving only objective k subject to the constraints, then

$$M_k = \operatorname*{Max}_{\underline{x}\in X} \{f_k(\underline{x})\} \qquad (2)$$

The optimal decision variables at this point is given by

$$\underline{x}_k^* = \{\underline{x} \,|\, f_k(\underline{x}) = M_k\} \qquad (3)$$

The other objective functions will take on values given by:

$$f_j^k = f_j(\underline{x}_k^*) \qquad (4)$$

The method of the STEM procedure involves the following steps. First, p single objective functions are solved subject the constraints. Each solution produces an optimal decision point $\underline{x}_k^*$ and an objective value $f(\underline{x}_k^*)$. Second, define the minimum value m_k that is attainable by objective k as:

$$m_k = \operatorname*{Min}_{j}\,(f_k^j) \qquad (5)$$

$[m_k, M_k]$ gives the range of values in which the final value of objective k is expected to lie subject to the constraints and the effect of all the other competing objectives. Third, define a utility function, U, over the range $[m_k, M_k]$ for each objective. These utility functions can take different shapes (see Figure 2) and is largely dependent on the preferences of the decision maker. They reflect the weights assigned by the decision maker to achieve different proportions of the range $[m_k, M_k]$. The range of U is taken to be [0,1] and is defined as:

$$U(m_k) = 0 \qquad (6)$$

$$U(M_k) = 1. \qquad (7)$$

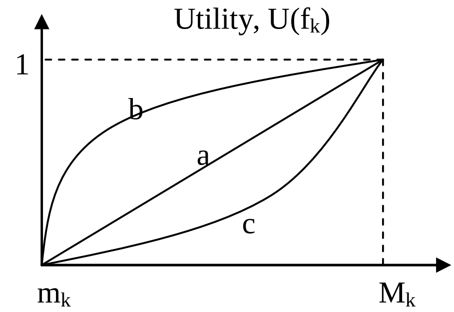

Figure 2: Shapes of the utility function, U.

Adopting the linear utility function, the utility U can be defined as:

$$U_k^j = U(f_k^j) = \frac{f_k^j - m_k}{M_k - m_k} \qquad (8)$$

We assume that the above form of the utility function is a true representation of the utility and further assume that they are additive. The best solution among the p single objective solutions is selected using the following relationship:

$$\operatorname*{Max}_{j}(UT(j)) = \operatorname*{Max}_{j}\Big(\sum_{k=1}^{p} U[\,f_k^j(\underline{x}_j^*)]\Big) \qquad (9)$$

If we denote the objective function that result from equation 9 by *s* then

$$UT^* = UT(s) \qquad (10)$$

UT^* ranges from 0 to p and represents the maximisation of the objective function that produces the maximum utility according to equation 8. The objective function s reaches its maximum possible value M_s and the other objectives have values given by f_k^s. We now begin an iterative procedure where p single objective solutions are sought with additional constraints. Except for the objective s, the following constraints are added to equation 1.

$$[f_k(\underline{x})]_{n+1} \geq [f_k^s(\underline{x}_s^*)]_n \quad \forall \quad k \neq s \tag{11}$$

And for the objective s:

$$[f_s(\underline{x})]_{n+1} \geq [f_s(\underline{x}_s^*)]_n - [\Delta f_s]_n \tag{12}$$

where n is the iteration number and Δf_s is an appropriate adjustment to the objective value s to allow room for the other objectives to improve. Δf_s is selected and revised at each iteration to satisfy feasibility of the optimisation procedure as well as considering the preferences of the decision maker.

3. OBJECTIVE FUNCTIONS AND CONSTRAINTS

The multi-objective problem described in this paper consists of three objective functions: maximizing net returns (NR), minimizing variable cost (VC) and minimizing total supplementary groundwater pumping requirements (TP) to meet crop demand from the irrigated areas. Conceptually, NR and VC may represent the view of agriculturalist while minimizing total pumping may be the desired goal to avoid groundwater mining and pollution of aquifers in situations where vertical segregation of aquifer salinity occur. The management options to achieve the above objectives consist of selection of an appropriate mix of crops, optimum level of groundwater pumping and appropriate allocation of water for irrigation and environment. Constraints imposed on the system include seasonal environmental flows targets. In addition, water allocation rules and pumping targets for each month are constraints imposed on the system.

The three objective functions were formulated as follows:

$$Max \quad NR = \sum_c CGM(c) \times X(c) - \sum_c \sum_m \{WREQ(c,m) \times X(c) \times C_w\} - C_p \times \sum_c \sum_m P(c,m) \tag{13}$$

$$Min\ VC = \sum_c \sum_m \left(X(c) \times WREQ(c,m) \times C_w \right) + \sum_c X(c) \times Vcost(c) \tag{14}$$

$$Min\ TP = \sum_c \sum_m P(c,m) \tag{15}$$

where *X(c)* = area of crop *c* (Ha), CGM(c) = gross margin for crop *c* ($), *WREQ(c,m)* = water requirement for crop *c* in month *m* (ML), C_w = total cost of water per unit volume ($/ML), C_p = cost of groundwater pumping and delivery ($/ML), *Vcost* = variable cost (such as fertilizer and pesticides applications) per hectare other than water cost for crop *c* and *P(c,m)* = volume of ground water pumped from irrigation areas for crop *c* in month *m* (ML).

Detailed description of constraints can be found in Xevi and Khan (2005).

3.1. THE HYPOTHETICAL IRRIGATION AREA

For the purpose of this paper, the irrigated area is divided into eight regions (Figure 3) with a total irrigable land of 121,808 ha and a potential for growing fourteen crops (rice, wheat, oats, barley, maize, canola, soybean, winter pasture, summer pasture, lucerne, vines, summer vegetables, winter vegetables, citrus and stone fruit). In the current analysis groundwater pumping from the irrigable area is permitted to satisfy crop water demand if surface water supplies are not sufficient. Licensed bores are located within the sub-catchment that use water for stock, domestic use and irrigation

Detailed descriptions of inflows, environmental requirements, crops and farm areas can be found in (Xevi and Khan, 2003; Xevi and Khan, 2005)

4. RESULTS

Three linear programming solutions were obtained at each iteration of the STEM process using GAMS software (Brooke et al., 1998), which corresponds to the three objective functions: maximizing net returns (NR), minimizing variable cost (VC) and minimizing total supplementary groundwater pumping requirements (TP).

Table 1. Initial pay-off matrix of single optimisation of objectives.

Objective		f_k^j		
j	symbol	1	2	3
1	NR(million$)	95.46	105.87	86.67
2	VC(million$)	48.37	57.85	81.16
3	TP (ML)	51.95	66.52	55.69
	M_k	95.46	105.87	86.67
	m_k	48.37	57.85	55.69
	D_k	47.09	48.01	30.98

Table 1 shows the results of the initial iteration (n=0) of single objective solutions and their corresponding f_k^j. Also, shown in the table is the maximum M_k, minimum m_k and the range of objective space $D_k = |M_k - m_k|$. Table 2 shows the values of the utility function given in equation 8 and the summations as is given in equation 9. From table 2, objective 3 (TP) has the highest summation value of 1.9 and is therefore the best objective chosen for the next iteration.

Table 2: Utility at initial stage of iterations (n=0).

Objective		$U_k^j = (f_k^j - m_k)/D_k$			$\sum_k U_k^j$
j	symbol	1	2	3	
1	NR	1	0	0	1
2	VC	0	1	0.18	1.18
3	TP	0.08	0.82	1	1.9

Table 3 shows the single objective solutions with constraints 11 and 12 imposed. The adjustment imposed on objective 3 (TP) is 14% of its range, D_k = 30.98 i.e. Δf_s = 4.31. Table 4 shows the corresponding values of the utility function. At this stage objective 1 (NR) is the best objective according to the criterion specified in equation 9 and 10. This process was continued to the third iteration and the progress is shown in Figures 4, 5 and 6 as the iterations marches toward a compromise solution. At iteration 3 (not shown) the final compromise solution was NR = $51.95 million, TC = $66.52 million and TP = 55700 ML and results from minimisation of total pumping (TP). At this point the net revenue (NR) only reached 7.5% of its possible range; TC reached 82% of its possible range.

Table 3. Pay-off matrix at second iteration of single optimisation of objectives. Values of objective 1 and 2 are in millions while objective 3 is in thousands of dollars

Objective		f_k^j		
j	symbol	1	2	3
1	NR(million$)	63.86	73.75	60.0
2	VC(million$)	51.25	64.28	60.0
3	TP(ML)	55.28	69.53	57.7
	M_k	63.86	73.75	60.0
	m_k	51.25	64.28	57.7
	D_k	12.61	9.47	3.3

Table 4. Utility at second iteration (n=1)

Objective		$U_k^j = (f_k^j - m_k)/D_k$			$\sum_k U_k^j$
j	symbol	1	2	3	
1	NR	0.33	0.67	0.86	1.86
2	VC	0.06	0.87	0.86	1.79
3	TP	0.15	0.76	0.93	1.84

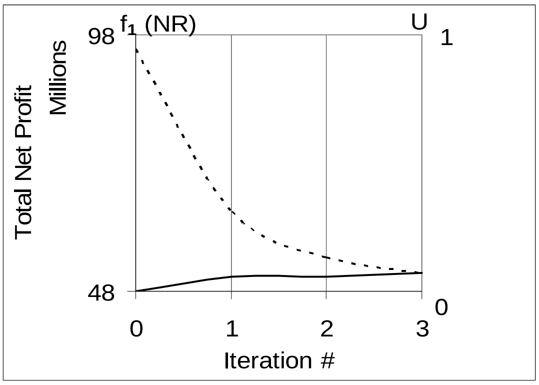

Figure 4. Iteration progress for NR (dotted line represents upper limit for objective function value M_k and the solid line represents lower limit of objective function value, (m_k)

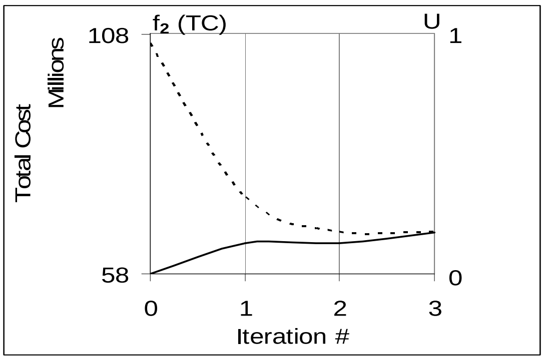

Figure 5. Iteration progress for TC (dotted line represents upper limit for objective function value M_k and the solid line represents lower limit of objective function value, m_k)

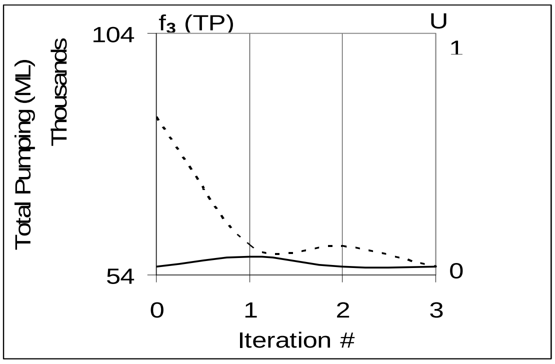

Figure 6. Iteration progress for TP (dotted line represents upper limit for objective function value Mk and the solid line represents lower limit of objective function value, mk)

5. CONCLUSION

A framework is presented from which multiple decisions that are in conflict can be made with tradeoffs. The tradeoffs' are entirely under the control of the decision maker and is able to direct preferences for one or the other objective. Points on the non-inferior set are generated through a set of single objective functions and constraints and one of these points is selected as the compromise solution. The procedure involves iterations where preferences are based on the objective space of previous iterations. The decision making process is entirely in the objective space and results are presented in the form graphs and tables of objective values and utility values. The choice of the values for adjusting the objective value is completely subjective and needs stakeholder inputs which affect the final compromised solution. A linear utility function was arbitrarily adopted in this study but there is scope for investigating and comparing the results from other utility functions. There is an extensive decision space that is not included in this paper. The decision space may be used by decision makers to affect their articulation of preferences but by far the objective space predominates in arriving at these preferences partly because their dimensions are considerably lower and can be analysed more easily.

6. ACKNOWLEDGEMENTS

The authors wish to acknowledge funding support from the CRC for Irrigation Futures and the Water for a Healthy Country Flagship.

7. REFERENCES

Alkan, D. and U. Shamir. (1980), Multiple objective planning of a regional water resource system. In: Operations Research in Agriculture and water resources. Eds. Yaron, B. and C. Tapiero. 439 - 465

Brooke A., D. Kendrick, A. Meeraus, R. Raman. (1998), GAMS A User's Guide. GAMS development Cooperation, Washington DC 20007 USA.

Benayoun, R., de Montgolfier, J., Tergny, J., and Taritchev, O. (1971), Linear programming with Multiple Objective Functions: STEP Method. Mathematical Programming, vol. 1, No 3 pp. 366-375.

Berbel, J., (1993), Risk programming in Agricultural Systems: A multiple criteria analysis. *Agricultural Systems,* 41, 275-288.

Characklis, GW, Griffin, RC & Bedient, PB (2005), 'Measuring the long-term regional benefits of salinity Reduction', Journal of Agricultural and Resource Economics, vol. 30, pp. 69-93.

Houk, E, Frasier, M & Schuck, E (2005), 'Irrigation technology decisions in the presence of waterlogging and soil salinity', Global Business and Economics Review, vol. 7, pp. 343-352.

Hussain, I, Mudasser, M, Hanjra, MA, Amrasinghe, U & Molden, D (2004), 'Improving wheat productivity in Pakistan: econometric analysis using panel data from Chaj in the upper Indus Basin', Water International, vol. 29, pp. 189-200.

Khan, S, Tariq, R, Yuanlai, C & Blackwell, J (2006), 'Can irrigation be sustainable?' Agricultural Water Management, vol. 80, pp. 87-99.

Piech, B. and T. Rehman, (1993), Application of Multiple Criteria Decision Making Methods to Farm Planning: A case Study. *Agricultural Systems,* 41, 305-319.

Ragan, GE, Young, RA & Makela, CJ (2000), 'New evidence on the economic benefits of controlling salinity in domestic water supplies', Water Resources Research, vol. 36, pp. 1087.

Tecle, A. (1998), A Multiobjective Decision Support System for Multiresource Forest Management. *Group Decision and Negotiation* 7, 23-40.

Wichelns, D (1999), 'An economic model of waterlogging and salinization in arid regions', Ecological Economics, vol. 30, pp. 475 - 491.

Wichelns, D (2002), 'An economic perspective on the potential gains from improvements in irrigation water management', Agricultural Water Management, vol. 52, pp. 233-248.

Xevi E. and Khan S. (2003), A Multi-Objective Optimization Approach to Water Management. MODSIM 2003. International Congress on Modelling and Simulation Proceedings, Townsville.14th-17th July. 4: 1615 – 1620

Xevi E. and Khan S. (2005), A Multi-Objective Optimization Approach to Water Management. Journal of Environmental Management (77) 269-277