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Regional Planning of Wastewater Reuse for Irrigation and River Rehabilitation

by

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REGIONAL PLANNING OF WASTEWATER REUSE FOR IRRIGATION AND RIVER REHABILITATION

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With some agri-environmental restrictions, municipal wastewater can be utilized for agricultural irrigation and river rehabilitation. This paper develops a single-year planning model for a region in Israel which consists of a city and three potential wastewater consumers. The model incorporates, in one endogenous system, the economic, physical and biological relationships in the water-soil-plant-environment system and its objective is to maximize the regional social welfare composed of the sum of agricultural and environmental net benefits. The model determines the optimal crop mix and the optimal allocation of the limited water and land resources among all potential users. Then, different allocation approaches from the concept of transferable utility games are applied to determine a reasonable and fair allocation of the additional net benefits which will be accepted by the players. The results support the collaboration among the economic entities and indicate economic and environmental advantages which can serve the decision-makers.

Keywords: Wastewater reuse, Allocation, Optimization Model, Transferable utility games.

1. INTRODUCTION

It is now well recognized that the sustainability of agriculture is directly linked to the efficiency of water use. Fresh water is undoubtedly one of the most limiting factors for agricultural production in arid and semi arid regions. As fresh water becomes scarce and competition with other sectors (i.e. urban, industrial and environmental) increases, farmers find themselves relying more and more on the utilization of marginal water resources (recycled and saline water).

In Israel, despite its modest role in the national product (1.8% of the GDP), agriculture consumes about 27% of the nation's limited freshwater supply. There is a consensus among policy-makers and water experts that the supply of potable water (i.e. urban consumption) should receive top priority (Zaslavski, 2001). Therefore, the supply of reclaimed sewage and other alternative sources is expected to grow substantially due to increases in water consumption in the growing domestic and industrial sectors, and the expansion of irrigation with recycled effluents (Di Pinto et al., 1999; Pereira et al., 2002). Indeed, a large-scale transition in agricultural water use, from good-quality fresh water to treated wastewater, is already taking place in Israel and it is expected that within a few years the wastewater will constitute about half of the total irrigation water (Water Commission, 2002). This shift requires the development of many more environmentally safe water-treatment plants, reservoirs and conveyance systems. In addition, under certain conditions, the use of municipal wastewater for river rehabilitation is also an effective means of wastewater removal combined with significant economic advantages (Fleischer and Tsur, 2000; Loomis et al., 2000).

This paper is aimed at developing and implementing models which describe the economic, environmental and organizational aspects of sharing different types of water (fresh, recycled) among two potential consumers -- the agricultural sector (irrigation) and the environmental sector (river rehabilitation), at a regional level.

The current research is divided into two parts. First, we develop a Planning Model which determines the optimal crop mix and the optimal allocation of the limited water and land resources among all potential users (Dinar and Yaron, 1986; Haruvy, 1998; Haouari and Azaiea, 2001). The model's objective is to maximize regional social welfare, which is composed of the sum of the agricultural and environmental net benefits (gross benefits minus relevant costs) in the examined region, while taking into consideration the impacts of salinity and nitrogen on the commercial yields of the various crops (Mass and Hoffman, 1977; Feinerman and Yaron, 1983) and the environmental damage associated with irrigation with recycled water over an unconfined aquifer. The model incorporates, in one endogenous system, the economic, physical and biological relationships in the water-soil-plant-environment system while taking into consideration the possibility of using recycled wastewater for river restoration. In this part, we expand the relevant optimization models currently available in the literature, such as Haruvy et al. (1999) and Dinar et al. (1986) by adding more realistic agri-environmental restrictions.

The result obtained from the Planning Model determines the total net benefits in the region that should be allocated among the assumed economic entities or players. Obviously, each player would like to have the largest possible share. Here we assume the following allocation procedure: all players reach a cooperative agreement about the basic principles (that should be anonymous, symmetrical, efficient and rational) of allocation, and then they nominate a benevolent middleman who determines the actual allocation, subject to the basic, agreed-upon principles. Specifically, we assume that these principles can be satisfied if the decisions of the middleman are based on an allocation scheme from the concept of transferable utility (TU) games[1] with application to problems similar to our current reserach (e.g., Dinar et al., 1986; Young, 1994; Lejano and Davos, 1995; Loehman, 1995). The different approaches are referred to the allocation of the additional net benefit (gross benefit minus the parties' stand-alone values) obtained in the examined region among the players.

The analysis is applied to the Sharon region in central Israel, which includes two cities [operating one wastewater-treatment plant (WWTP)], the Yarqon River Authority (RA) and two groups of farmers. The motivation for regional cooperation among these economic entities is concealed in the economic and environmental advantages related to the reuse of recycled wastewater for irrigation and river rehabilitation. The farmers might be able to increase their irrigated areas and benefits and the RA is expected to increase its streamflow and benefits. The rest of the paper is organized as follows: Section 2 develops the regional mathematical-programming planning model and presents the motivation for cooperation between the various economic entities. The planning model is applied to a situation in Israel and the results are also presented in Section 2. Then, in Section 3 we analyze potential ways to allocate the additional net benefits resulted from regional cooperation between the involved economic entities (players). The allocation schemes of the net benefits are applied to the results obtained in the previous section. The concluding remarks in Section 4 end the paper.

2. A Regional Planning Model

The objective of the model is to maximize the sum of net benefits in the examined region, subject to a given supply of wastewater, environmental and health regulations, and the farmers' capability and willingness to utilize the recycled wastewater for crop irrigation. The impacts of salinity and nitrogen on the commercial yields of the various crops and the environmental damage associated with irrigation with recycled water over an aquifer are taken into consideration.

The following economic entities or "players" are involved: (1) the city that owns a WWTP is "the effluent producer"; (2) a river authority responsible for the restoration of a river that crosses the region and runs to the sea; (3) a group of farmers located (geographically) close to the WWTP -- "the nearby farmers" and (4) a group of farmers

[1] Also known as a cooperative games with side payments.

located far from the WWTP -- "the distant farmers". The two groups of farmers and the RA are the potential consumers of the city's recycled effluent.

The motivation for regional cooperation among these players is concealed in the economic and environmental advantages related to recycled wastewater reuse for irrigation and river rehabilitation. Utilization of recycled wastewater may increase the net benefits to the farmers and the utility of the RA.

The economic analysis refers to a period of one year, with all long-term revenues and costs expressed on an annual basis. However, the model takes into account the possible effects of present recycled wastewater reuse decisions on the long-term salt accumulation in the groundwater aquifer. We assume a central planner (CP) who operates under certainty conditions. The decisions of the CP can be divided into two major groups: (1) choosing the optimal organizational structure that yields the maximum benefit in the region (see Figure 1) and (2) determining the recycled wastewater and freshwater allocation to the involved players in the region. The decisions of the CP are subject to various agricultural, environmental and health constraints that are presented below.

The objective of the CP is to allocate the water (recycled wastewater and fresh water) among the potential consumers such that **total** net benefits are maximized in the region. The allocation of the net benefits among the four players is not in the discretion of the CP and is determined in a later stage.

We assume that the effluent can be purified to two quality levels: (a) secondary level -- the current low-quality level at the WWTP and (b) tertiary level -- the upgraded level. According to the conclusions of the Halperin Committee (The Ministry of Health, 1999), the tertiary level is the minimal quality of wastewater purification that is safe for ecological uses (i.e. river rehabilitation), for disposal in the sea and for the irrigation of all crops without toxic accumulation in the soil and leaching into the aquifer. Irrigation with secondary-level recycled wastewater is not allowed over an aquifer in order to avoid toxic percolation. In addition, this low-quality water cannot be used for irrigating some crops, such as vegetables, deciduous plants, artichoke, etc.

For the sake of clarity, the possible water allocations and its associated symbols are summarized in Table 1.

Table 1: Water allocation schemes

j/i	**1**	**2**	**3**	**4**	**Description**
1	---	W^{12}	W^{13}	---	The amount of wastewater that the city will purify to secondary (*j* = 2) and tertiary (*j* = 3) levels
2	---	---	$W^{23} = W^{R}$	---	The amount of tertiary wastewater that will be allocated to the RA
3	W^{31}	W^{32}	W^{33}	W^{34}	The amount of water from the various sources that will be allocated to the nearby farmers
4	W^{41}	W^{42}	W^{43}	W^{44}	The amount of water from the various sources that will be allocated to the distant farmers
5	---	---	$W^{53} = W^{M}$	---	The amount of tertiary wastewater that will be disposed of by release into the sea

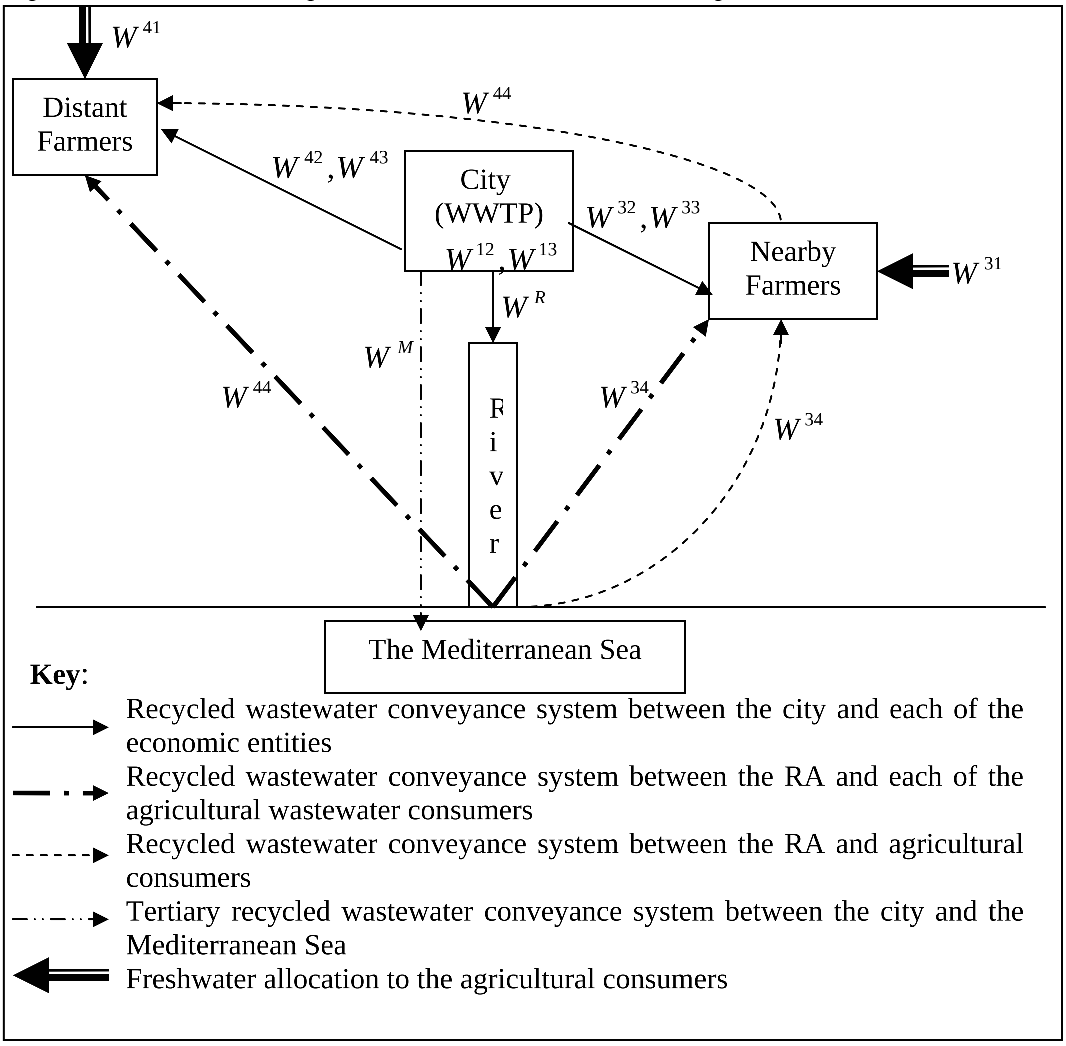
i - The economic entity in the region (*i* = 1 represents the city; *i* = 2 represents the RA; *i* = 3 represents the nearby farmers; *i* = 4 represents the distant farmers and *i* = 5 represents the sea).

j - The water sources in the region (*j* = 1 represents fresh water available to the groups of farmers; *j* = 2 and *j* = 3 represent secondary and tertiary recycled wastewater, respectively,

and $j = 4$ represents the tertiary recycled wastewater that is allocated to the river.
W^{ij} - Water allocation (in cubic meters) from source j to economic entity i.

A schematic description of the possible organizational alternatives faced by the CP is shown in Figure 1.

Figure 1: The Possible Organizational Alternatives in the Region



Specifically, we analyze the following organizational alternatives:

1. No cooperation: each economic entity acts independently
2. Cooperation between the city and one of the entities
3. Cooperation between the city and two of the entities[2]
4. Cooperation between all entities within the region (the grand coalition).

We assume that, in the alternatives where the city cooperates with the RA, the possibility exists of there being no need to build a conveyance system between the city and the sea (the recycled wastewater will be disposed of at sea, via the river). We now describe in relative length the characteristics and assumptions associated with the assumed economic entities.

[2] In this alternative we also examine the possibility of conveying only tertiary wastewater from the river to one (or more) group(s) of farmer(s) while taking into consideration the related costs.

The City and the Wastewater Treatment Plant

The city is obligated by law to purify and discharge the wastewater from its jurisdiction while satisfying several environmental and health requirements, such as threshold levels of BOD, COD and TSS[3] (Water Law, 1959; The Ministry of Health, 1999; Water Commission, 1999). We assume that the city is obligated by law to dispose of its <u>entire</u> exogenously given amount of wastewater ($\overline{W}$). In other words, at the end of the allocation process, no wastewater is left in the city's jurisdiction. Formally,

(1) $$\overline{W} = \sum_{i=3}^{4}\sum_{j=2}^{3} W^{ij} + W^{R} + W^{M}$$

As mentioned, we assume two wastewater quality levels: (a) secondary level and (b) tertiary level

The agricultural (i.e. irrigation) and ecological (i.e. river rehabilitation) advantages of reusing wastewater that has been purified to the tertiary level, motivated us to examine the possibility of upgrading the current WWTP to be able to purify to this level (in addition to the current, secondary level), implying,

(2) $$\overline{W} = W^{13} + W^{12}$$

The operating cost (in dollars) of conveying 1 m^3 of recycled wastewater of quality *j* (*j* = 2,3) to the i^{th} customer $(i \neq 1)$ is denoted by e^{ij}, and it depends, among others things, on the location of the potential users (distance from the city and topography), pipe pressures, pumping costs, energy costs, and more. The purification cost (in dollars per m^3) is α^{j} (*j* = 2,3), and it includes the operational and maintenance costs, energy costs, and costs of materials and activated-sludge disposal.

The annual equivalent investment cost (in dollars) of building a new conveyance system from the WWTP to the potential users is F_1^i, $i \neq 1$, taking into consideration the distance of the potential users from the city, the pipe length, and the topography. The annual equivalent cost (in dollars) of upgrading the current purification level of the WWTP from secondary to tertiary is denoted by *E* and it includes the costs of planning, designing and building, purchasing materials, etc.

The city's effluent causes health and environmental damage. Without loss of generality, we assume that the additional net benefit to the city (in monetary terms), EU^1, from wastewater discharge is equal to the cost of conveying it to the sea,[4] namely,

(3) $$EU^{1} = e^{53} W^{M}$$

The total cost associated with purifying and discharging effluent from the city excluding the additional profit to the city, EU^1, is given by:

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[3] BOD = biochemical oxygen demand; COD = chemical oxygen demand; TSS = total suspended solids.
[4] The change in the city's benefit from discharging effluent from its jurisdiction has no effect on the profits and/or on the amount of water (fresh and wastewater) allocated to the other economic entities in the region (i.e. farmers and RA).

(4) $$TC^1 = \sum_{i=2}^{4}\sum_{j=2}^{3}\left[\left(e^{ij} + \alpha^j\right)\cdot\left(W^{ij} + W^R + W^M\right)\right] + \sum_{i=2}^{5} F_1^i + E$$

Note that in the case in which the city does not allocate wastewater to the other economic entities, $W^{ij} = W^R = 0$ for *j* = 2,3 and *i* = 3,4, all the recycled effluent (tertiary level) will be disposed of in the sea [see (1)], yielding:

(5) $$TC_0^1 = \alpha^3 \cdot W^M + F_1^5 + E$$

where TC_0^1 can be viewed as the city's "threat alternative" or "zero alternative" since the entire purification and discharge costs are born by the city.

The River Authority

The RA has potential ecological benefits to gain from utilizing the city's recycled wastewater. As already mentioned, the RA can use only tertiary wastewater and it may also convey recycled wastewater to the agricultural groups[5]. This activity requires investing in conveyance structures from the RA to the two groups of farmers. Equation (6) presents the RA's benefit from the flow of recycled wastewater in the river:

(6) $$EU^2 = uW^R,$$

where u is an estimation of the benefit (in dollars) from a flow of 1 m^3 of tertiary recycled wastewater in the river.

Adding the RA into the regional cooperation between the city and the farmers imposes the following additional major costs: e^{i4} -- the operating cost (in dollars) of conveying 1 m^3 of tertiary recycled wastewater to the i^{th} agricultural consumer, $(i = 3,4)$. This cost depends on the farmers' distance from the river's downstream, on pipe pressures, on pumping and energy costs, etc.

The annual equivalent investment costs (in dollars) for building a new conveyance system from the RA to the nearby farmers and to the distant farmers are denoted by F_2^3 and F_2^4 , respectively.

The total cost, TC^R, associated with building a new conveyance system and transferring the tertiary recycled wastewater from the RA to the potential users is:

(7) $$TC^R = c^3 W^R + \sum_{i=3}^{4}\left(e^{i4}W^{i4} + F_2^i\right)$$

By subtracting (7) from (6), we get the RA's benefit from utilizing the city's tertiary recycled wastewater,

(8) $$\pi^2 = \sum_{i=3}^{4}\left[u \cdot W^R + e^{i4} \cdot W^{i4} - F_2^i\right].$$

[5] This alternative can be applied only when $W^R > 0$.

The Farmers

The two assumed groups of farmers in the region differ in their location, the size of agricultural plot, freshwater quotas and crop mixes, among other things.

Each farmer has a freshwater quota (in m^3) of $\overline{Q}^i$ (i = 3,4). He is endowed with $\overline{X}^i_g$ hectares (ha) of agricultural land, some of which is located above a groundwater aquifer (indexed by g = 1) and some of which is not (indexed by g = 2), and he can choose to grow up to N crops. The farmer's net benefit from utilizing recycled wastewater for irrigation is:

$$\text{(9)} \qquad \pi^i = \sum_{n=1}^{8}\sum_{g=1}^{2}\sum_{j=1}^{4} p_n^{ij} x_{ng}^{ij} - \sum_{n=1}^{3}\sum_{g=1}^{2} h_n^i \cdot \tilde{x}_{ng}^i - c_W W^{i1} \quad , i = 3,4$$

where:

p_n^{ij} - net income (in dollars) from 1 ha of crop n (n = 1,…,N), irrigated with water from source j minus the fixed and variable costs, not including the expenses associated with recycled wastewater use (see Appendix I).

x_{ng}^{ij} - the area (ha) of crop n grown by the i^{th} farmer irrigated with water from source j and located above (g = 1) or not (g = 2) the relevant aquifer (a decision variable).

h_n^i - the cost of uprooting existing orchard n (n = 1,2,3) grown by farmer i (in dollars per ha).

$\tilde{x}_{ng}^i$ - the uprooted area (ha) associated with the n^{th} orchard (n = 1,2,3) grown in area g by farmer i (a decision variable).

c_W - the cost of fresh water diverted for agricultural use (in dollars per m^3).

The Planning Constraints

In this subsection, we formulate the restrictions faced by the CP on the choice of the decision variables, W^{ij}, x_{ng}^{ij}, and $\tilde{x}_{ng}^i$, which maximize the regional objective function.

The total land area, $\overline{X}^i_g$, of the i^{th} farmer is predetermined, implying,

$$\text{(10)} \qquad \overline{X}^i_g - \sum_{j=1}^{4}\sum_{n=1}^{8}\sum_{g=1}^{2} x_{ng}^{ij} \geq 0 \quad , \; i = 3,4$$

To avoid significant deviation of the model's results from the actual situation in the region, we limit the deviations to lying between the current crop area and the ones recommended by the Planning Model, implying,

$$\text{(11)} \qquad \overline{b}_n^i - x_{ng}^{ij} \geq 0 \quad , n = 4,\ldots,8$$

$$\text{(12)} \qquad \underline{b}_n^i - x_{ng}^{ij} \leq 0 \quad , n = 4,\ldots,8 ,$$

where parameters $\overline{b}_n^i$ and $\underline{b}_n^i$ denote the maximum and minimum land area (in ha) that can be planted for crop n, n = 4,…,8, by farmer i, respectively.

We also assume the possibility of allowing uprooting of orchards (n = 1,2,3), up to a level of m% of the current area, and cultivating other crops instead.

$$\text{(13)} \qquad m \cdot \overline{b}_n^i - \tilde{x}_{ng}^i \geq 0 \quad , \; n = 1,2,3$$

The equations of orchard balances are given by

(14) $$\overline{b}_n^i - \left(x_{ng}^{ij} + \tilde{x}_{ng}^{i} \right) = 0 \quad , n = 1,2,3$$

The total amount of wastewater (in m^3) "supplied" by the city is common knowledge for all the players in the region [see (1)], and it is completely exhausted by all possible users (including the sea):

(15) $$\overline{W} - \sum_{i=3}^{4} \sum_{j=2}^{3} W^{ij} - W^R - W^M = 0$$

The wastewater can be utilized following secondary and/or tertiary[6] purification, implying:

(16) $$\overline{W} - W^{13} - W^{12} = 0$$

As already mentioned, tertiary wastewater, once it is flowing in the river, is also potentially available for irrigation by the two groups of farmers in the region, implying:

(17) $$W^R - W^{34} - W^{44} \geq 0$$

The farmers' wastewater balances are

(18) $$W^{ij} - \sum_{g=1}^{2} \sum_{n=1}^{8} w_{ng}^{ij} x_{ng}^{ij} = 0, \; i = 3,4 \; ; j = 2,3,4$$

where w_{ng}^{ij} is the annual amount of water required for irrigating 1 ha of crop *n* located in *g* by farmer *i*. We assume that the amount of w_{ng}^{ij} is predetermined via commonly used best-management agricultural practices and independent of the source (fresh, secondary or tertiary) of water.

Expressions (19) and (20) describe the freshwater quota restrictions available to the nearby and distant farmers,[7] respectively.

(19) $$\overline{Q}^3 - W^{31} \geq 0$$

(20) $$\overline{Q}^4 - W^{41} \geq 0$$

Irrigating with secondary wastewater above an aquifer is forbidden. According to the Halperin Committee report (Ministry of Health, 1999), there are several crops (citrus, avocado and potatoes) that can be irrigated with secondary (and obviously, with tertiary) wastewater, but of course not if they are grown above an aquifer (g = 1). Irrigating these three types of crops with tertiary and secondary wastewater are presented in equations (21) and (22), respectively,

[6] Requiring upgrading of the WWTP.

[7] We use expression (18) to calculate W^{i1} for all *j* and *i* = 3, 4.

(21) $$\sum_{i=3}^{4}\sum_{j=3}^{4} W^{ij} - \sum_{i=3}^{4}\sum_{n=1,2,7}\sum_{g=1}^{2} x_{ng}^{i3} \cdot w_{ng}^{i3} \geq 0$$

(22) $$W^{12} - \sum_{i=3}^{4}\sum_{n=1,2,7} x_{n2}^{i2} \cdot w_{n2}^{i2} \geq 0$$

All the decision variables must be non-negative for all *n, j, g*,

(23) $$x_{ng}^{ij}, \tilde{x}_{ng}^{i}, W^{ij} \geq 0$$

The Central Planner's Problem and Potential Cooperation

The CP's objective is to maximize the social welfare or total benefits in the region, while taking into consideration the various possibilities of cooperation among the economic entities. We assume certainty conditions, meaning that the CP knows the objective function of each player and can calculate the profitability of adding him to each of the various potential regional collaborations.

The optimization model relates to potential cooperation between the city, the wastewater producer, and the three potential consumers (nearby farmers, distant farmers and the RA). The motivation for regional cooperation among these economic entities or players stems from the economic and environmental advantages associated with wastewater reuse for irrigation and river rehabilitation. Therefore, any coalition which does not include the city is worthless or not profitable.

Let *G* denote the group of all wastewater consumers in the region, meaning: *G* = (2,3,4), and let *s* represent any partial group of consumers, excluding the city. Namely, *s* is a subgroup of *G*, $s \subseteq G$. Collaboration between every subgroup, *s*, and the city, $s \cup (1)$, creates a potential coalition, $S = \{s \cup (1)\}$, the relative profitability of which will be evaluated by the CP.

The stand-alone coalitions (no cooperation) are {i}, *i* = 1,2,3,4. These alternatives represent the profit of each economic entity when acting alone. We determine the alternative of a collaboration between all the players in the region as the Grand Coalition, $\overline{N} = \{(1) \cup G\}$, $(S \subseteq \overline{N})$.

The CP's problem is to determine the level of the decision variables: W^{ij}, x_{ng}^{ij}, $\tilde{x}_{ng}^{i}$ for all *i*, *j* and *g* while choosing the organizational structure that maximizes the objective function for a (feasible) coalition *s* in the region. The sum of expressions (6) and (9) minus expression (4) is given by

(24) $$\underset{W^{ij}, x_{ng}^{ij}, \tilde{x}_{ng}^{i}}{\Pi^{S}} = \sum_{i=2}^{4} \pi^{i} - TC^{1}$$ For all *i, j, n, g* subject to constraints (10)-(23).

Empirical Application of the Planning Model

The analysis is applied to a situation in the Sharon region in central Israel. The region consists of two cities (Kfar Saba and Hod Ha'sharon) which operate one WWTP, the RA and two groups of farmers. Currently, the WWTP supplies 8 million m^3 of wastewater of a given quality (secondary treatment: BOD = 30, TSS = 20). The Yarqon River is the second biggest river in Israel and it runs 2 km southwest of the WWTP gate. The current low-quality (i.e. secondary) wastewater makes a negligible contribution to the river's rehabilitation. To obtain a positive environmental contribution, the CP must consider the possibility of upgrading the WWTP purification to a tertiary level (BOD = 10, TSS = 10). In the current study, we assume that each cubic meter of tertiary wastewater flowing in the Yarqon River contributes 0.32 dollars to the RA[8] (Kivun 2002, 2004; Rosenthal and Tsaban, 1999).

The conveyance and treatment costs were calculated using functional forms developed by the Israeli Water Commission[9] and by Eden (1999) on energy costs, and relevant information obtained via personal communication with the directors of the WWTP. The costs of building new conveyance infrastructures and of upgrading the current level of purification at the WWTP are presented in Table 2.

Table 2: The costs of building new conveyance systems and upgrading the current WWTP (in million dollars[10])

	From the city		From the RA	
	Total	**Annual return**	**Total**	**Annual return**
Conveyance system to nearby farmers (3)	0.34	0.05	0.91	0.13
Conveyance system to distant farmers (4)	0.67	0.095	1.565	0.22
Conveyance system to (3) and (4)	1	0.14	1.565	0.22
Conveyance system to the RA	0.18	0.025	------	------
Conveyance system to the Sea	0.91	0.13	------	------
	Total		**Annual return**	
Upgrading the current WWTP	8.3		1.18	

The farmers differ in their land area, cropping patterns, freshwater quotas, orchard areas and distance from the WWTP, as presented in Table 3:

Table 3: Farmers' characteristics

	Freshwater quotas (MCM)	**Cultivated area (in ha)**	**Orchard area (in ha)**	**Distance from the WWTP (km)**
Nearby farmers	1.635	400.7	198.2	4
Distant farmers	1,690	488.9	148	8

[8] In the draft submitted to the Israeli Nature and Parks Authority in 2004 (Kivun, 2004), it was estimated that the value of future visits and business development of the Yarqon is equal to 17 million dollars per year. The equivalent costs associated with the Yarqon's maintenance, RA operation and land uses is equal to 10.6 million dollars. In other words, the Yarqon RA benefits by about 6.4 million dollars per year. The above analysis refers to the case in which 20 M^3 of water is flowing in the river. Thus, each cubic meter of tertiary wastewater flowing in the Yarqon River makes a contribution of 0.32 dollars to the RA.

[9] The functional relationships developed by the Water Commission take into consideration pipe length, pipe pressure, and location (distant and topography).

[10] All monetary values are in constant December 2002 dollars.

The soil salinity level used in this study to calculate crop-yield losses is approximated by the simple average of the salinity level at the beginning and end of the irrigation season and is dependent on the quantity and the quality of the irrigation water. The yield loss function and coefficients in our study were borrowed from Mass and Hoffman (1977), and Feinerman and Yaron (1983). Calculation of crop budgets are based on publications of The Ministry of Agriculture (2002), Gal et al. (2000), Gal and Madleg (2000), Gal and Shpigel (2002), Yesharim and Salmon (2003), The Central Bureau of Statistics (2002), and The Ministry of Agriculture and Rural Development (2001).

Results

Regional cooperation can be established among the city and one or more of the wastewater consumers. Therefore, the number of a priori feasible coalitions in the region is 11 (less than the potential number of 2^4-1):

Non-cooperative coalitions (i.e. stand alone)	(1), (2), (3), (4)
Partial coalitions	(1,2), (1,3), (1,4), (1,2,3), (1,2,4), (1,3,4)
Grand coalition	(1,2,3,4)

The CP applies the optimization model [i.e. the objective function in (24) subject to restrictions (10)-(23)] to each of the feasible coalitions,[11] *s*, in the region. The results are summarized in Table 4.

Table 4: Total value of any feasible coalition in the optimal solution, the sum of players' stand-alone values in the coalition and the net benefit values of the coalitions (in million dollars)

	Column 1	**Column 2**	**Column 3**
Coalitions (i), (s)	**The coalition value** Π^S	**The summation of players' stand-alone income in coalition s** $\sum_1^4 \pi(i)$	**The additional net benefit of a coalition** $v(S)$
(1)	-3.31	-3.31	0.00
(2)	0.00	0.00	0.00
(3)	0.42	0.42	0.00
(4)	0.61	0.61	0.00
(1,2)	-0.58	-3.31	2.73
(1,3)	-2.52	-2.88	0.36
(1,4)	-2.16	-2.7	0.54
(1,2,3)	0.06	-2.88	2.94
(1,2,4)	0.32	-2.7	3.02
(1,3,4)	-1.37	-2.27	0.9
(1,2,3,4)	1.1	-2.27	3.38

Column 1 is the value of coalition(s) obtained from the optimization model.

[11] As mentioned, we assume that the added value of coalitions that do not include the city is zero [i.e. the value of coalitions (2, 3); (2, 4); (3, 4); (2, 3, 4) is zero].

Column 2 is the sum of the "stand-alone" values of each coalition member.
Column 3 is the difference between column 1 and column 2. In other words, *v(s)* is the additional net profit of any feasible coalition *s*.

The empirical analysis focuses on the monetary incentive for cooperation between the city and some or all of the wastewater consumers. It is shown that acting alone (i.e. non-cooperatively) is not a desirable solution. The highest additional net profit is achieved under the grand coalition -- 3.38 million dollars (Table 4), and therefore a grand coalition will be preferred by the CP.

Moreover, the optimal cooperative solution enables the farmer (or each group of farmers) to reallocate his freshwater quota more efficiently, to cultivate new land areas without uprooting orchards and to expand the area planted for crops which can be irrigated only with fresh water or with wastewater purified to a tertiary level (the total cultivated area in the region is increased by 23% relative to the non-cooperative situation, see Table 5). In addition, the use of tertiary wastewater by the farmers reduces the amount of irrigation with the scarce fresh water by 1.1 M^3, compared to the non-cooperative scheme, as illustrated in Table 6.

Table 5: Cultivated area allocation under the extreme alternatives[12] (in ha)

Crops (N) Coalitions	Distant Farmers		Nearby Farmers	
	(1,2,3,4)	**(4)**	**(1,2,3,4)**	**(3)**
1. Citrus	93.9	70.4	83.5	62.7
2. Avocado	54.1	40.6	---	---
3. Deciduous	---	---	125.1	93.9
4. Watermelon	93.8	56.5	---	---
5. Artichoke	---	---	62.5	62.5
6. Green plants	58.8	35.3	---	---
7. Potatoes	90	54	66.3	39.8
8. Animal feed (corn)	98.3	137.5	63.3	70
Total orchard uprooting	0	37	0	51.9
Total area irrigated with wastewater	331.8	0	233.6	0
Total cultivated area	488.9	394.3	400.7	328.9

Table 6: Water allocation under the extreme alternatives (in M^3)

Data Coalition	Distant Farmers		Nearby Farmers	
	(1,2,3,4)	**(4)**	**(1,2,3,4)**	**(3)**
Freshwater	0.98	1.69	1.25	1.635
Tertiary wastewater from the RA	1.55	0	0.88	0
Total	**2.53**	**1.69**	**2.13**	**1.635**

Tables 5 and 6 present the major changes for each group of farmers which are induced by the cooperation. The nearby farmers increase the amount of irrigation water by 0.88 M^3 of tertiary wastewater and their irrigated area increases from 328.9 to 400.7 ha. The usage of fresh water by these farmers decreases by 0.385 M^3. The distant farmers increase the amount of irrigation water by 1.55 M^3 of tertiary wastewater and their irrigated area increases from 394.3 to 488.9 ha. The usage of fresh water by these farmers decreases by 0.71 M^3.

[12] Coalitions of the farmers standing alone and the grand coalition [i.e. (3), (4), (1,2,3,4)].

3. Allocation of the Additional Net Profits among the Economic Entities Based on Game Theory Principles

The solutions presented in the previous section suggest that regional cooperation yields economic advantages and environmental benefits to the region as a whole. Although the proposed solution (i.e. a grand coalition) is economically efficient, it may be rejected by one or more of the economic entities in the region unless an acceptable allocation scheme is mutually agreed upon. Since the quota of fresh water is not transferable by law in Israel, the only way to affect the distribution of the additional regional net benefit from cooperation is through direct monetary transfers (side payments).

Implementation of the conventional competitive rule, i.e. that each wastewater user should pay according to the marginal treatment and conveyance cost, might provide a possible allocation scheme. But our analysis assumes only four economic entities which makes a free-market solution impractical. On the other hand, the small number of players calls for examining potential agreements and coalitions among some or all of them. Therefore, we examine and compare different allocation schemes which are based on commonly used concepts from the game theory literature, such as the Core, the Shapley value, and the Nucleolus.

The Characteristic Function

The regional Planning Model can be applied to every group or coalition of players in the region. The value of the objective function for every group of players minus the sum of the "stand-alone"[13] values of the groups' members is defined as the characteristic function of the coalition, $v(S)$ (see Table 4). A characteristic function of a coalition in a cooperative game identifies the share of the coalition in the total value of the game. In our study, a positive value of the characteristic function implies that it is profitable for the coalition members to participate in the cooperative game. Equation (25) defines the characteristic function of a normalized game where the middleman.

(25) $$v(S) = \pi(S) - \sum_{i \in S} \pi(i)$$

Here $\pi(S)$ is equal to Π^S derived in the Planning Model [see (24)]. Note that $v(i) = 0$ for all *i*. It is also assumed that $v(\phi) = 0$, where ϕ is the empty coalition and $v(\overline{N})$ represents the value of the grand coalition. The values of the characteristic function in our case are presented in Table 4 (Column 3).

In many cases, the characteristic function has one or more of the following properties: economy of scale, convexity, super additivity, or at least it is "zero-normalized".[14] The existence of at least one of the above characteristics guarantees that the grand coalition, $(\overline{N})$, will be the optimal solution.

We now present the desirable characteristics of our characteristic function, $v(S)$, which are required for our analysis below.

a. **Efficiency**: The optimal allocation is a vector $x = (x_1, x_2, x_3, x_4)$, where x_i denotes the additional net profit allocated to player i and satisfies:

[13] The player's value (benefit) when acting alone (does not cooperate).
[14] The value of coalitions which do not include the dominant player (the city in our case) is equal to zero.

(26) $$\sum_{i=1}^{4} x_i = v\left(\overline{N}\right)$$

Equation (26) guarantees the efficient allocation of <u>all</u> additional net profits among all the players in the region.[15]

b. **Super Additivity:** The motivation for cooperation is due to the ability of a certain group (coalition) to improve its position by collaborating with other groups:

(27) $v(S \cup T) \geq v(S) + v(T)$, where S and T represent different coalitions.

The value from merging two different coalitions is at least as large as the value of those coalitions when acting alone.

c. **Monotonicity:** The function *V* is not negative and monotonically increasing in *S*, implying that the additional net profits increase when more players participate in the coalition:

(28) $v(S) \leq v(T)$ For all $S \subseteq T$

Note that $v\left(\overline{N}\right)$ is the highest possible value of function *V* (in other words, $\left(\overline{N}\right)$ is the most efficient allocation)**.**

d. **Convexity:**

(29) $v(S \cap T) + v(S \cup T) \geq v(S) + v(T)$ where S and T are not necessarily different.

As already mentioned, without the city's wastewater, there is no motivation for regional cooperation. Therefore, the number of feasible coalitions in the region is 11 (see Table 4). Formally, a coalition which does not include player 1 (the city) will satisfy equation (27) only with equality or [see (25)] the value $v(S)$ of such a coalition is zero.

The Core

The core of the game considered here is composed of the set of all possible allocations of additional net profits which are not dominated by any other allocation set. The negotiation set of the cooperative game is composed of allocations that fulfill the requirement of individual rationality, group rationality and joint efficiency (no surpluses are left). The core's equations and the values of the characteristic function are presented in Table 7.

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[15] In the case where $\sum_{i=1}^{4} x_i > v\left(\overline{N}\right)$, the allocation of the total net profits to the players exceeds the total net profit of the grand coalition, therefore it is not possible. In the case where $\sum_{i=1}^{4} x_i < v\left(\overline{N}\right)$, we receive an inefficient allocation (unexploited surplus is remaining). Therefore we use the equal sign.

Table 7: The core and the characteristic function

	The core equations	The characteristic function $v(S)$	Requirements
i	$x_1 + x_2 + x_3 + x_4 = v(1,2,3,4)$	3.38	**Joint efficiency**
ii	$x_1 + x_2 + x_3 \geq v(1,2,3)$	2.94	**Group rationality**
iii	$x_1 + x_2 + x_4 \geq v(1,2,4)$	3.02	
iv	$x_1 + x_3 + x_4 \geq v(1,3,4)$	0.9	
v	$x_1 + x_2 \geq v(1,2)$	2.73	
vi	$x_1 + x_3 \geq v(1,3)$	0.36	
vii	$x_1 + x_4 \geq v(1,4)$	0.54	
viii	$x_1 \geq v(1)$	0.00	**Individual rationality**
ix	$x_2 \geq v(2)$	0.00	
x	$x_3 \geq v(3)$	0.00	
xi	$x_4 \geq v(4)$	0.00	

The core of this game is a four-dimensional polyhedron and due to its relatively small dimension, it can be easily shown that the game is monotonic and super additive, i.e. satisfies equations (28) and (27), respectively. However, a sufficient condition for a non-empty core is the convexity of the game and, unfortunately, the game here is not considered convex.[16] Nevertheless, by implementing the Shapley-Bondareva theorem (Shapley, 1967), we prove the existence of a non-empty core (see Appendix II).

The Nucleolus

In our study, the core does exist but is too large and leaves the additional net benefit-allocation problem open for further bargaining. A possible approach to reducing the large number of possibilities to a unique allocation is by calculating the nucleolus (see: Maschler, 1992; Friedman, 1990; Schmeidler, 1969). The nucleolus can be interpreted as the allocation which maximizes the minimal possible objection to the allocation for any of the coalitions; it is a max-min solution. The extent of the objection is measured by the "excess", $e(S,x)$, or by the difference,

$$(30) \qquad e(S,x) = v(S) - \sum_{i \in S} x_i$$

In other words, the value $e(S,x)$ is the difference between what the members of S could get if they bestirred themselves and exerted the power of S, and what they are getting in the imputation *x*. So, it is a measure of the unhappiness of S with *x*. The goal is to find the imputation(s) which will maximize the smallest of the $e(S,x)$'s. The nucleolus solution can be obtained via a lexicographical ordering. In the particular case considered here, the nucleolus of the regional game is obtained after solving the following "excess balance"

$$(31) \qquad D_{ij}(x) = D_{ji}(x) \qquad \forall i, j \in N$$

[16] Expression (29) does not hold, for example for S = (1, 3) and T = (1, 4). Therefore the game is not convex.

D_{ij} is, in fact, a function that minimizes the allocation surpluses (excess) created in coalitions where player *i* operates without collaborating with player *j*, for $i \neq j$. Thus, for example, when *i* = 1 and *j* = 2, the function D_{ij} receives the following form: $D_{12} = \max\{-x_1, v(1,3,4) - x_1 - x_3 - x_4, v(1,3) - x_1 - x_3, v(1,4) - x_1 - x_4\}$. Similarly, we denote D_{ji} as the case in which player j operates without collaborating with player *i*.

Substituting the values of the characteristic functions (see Table 7) in equation (31) for all pairs of players (a total of three!) and solving it simultaneously yields a unique solution for our nucleolus: $Nuc(x^*) = (1.74, 1.24, 0.18, 0.22)$.

The nucleolus solution gives player 1 the largest relative strength in the examined region and therefore, he receives the highest monetary allocation.

The nucleolus solution (as well as the Kernel solution in our case[17]) is associated with desirable characteristics which make it an attractive allocation for the regional players (e.g. Maschler, 1992; Young, 1994): (a) it provides a unique solution; (b) it is included in the core of the game and therefore possesses its desirable characteristics (individual rationality, group rationality and efficiency); (c) it is anonymous (symmetrical players receive the same allocation); (d) combining dummy players into the regional game will not affect the solution (i.e. dummy players will gain their stand-alone value); and (e) it makes sense: players' gains reflect their relative strengths in the game.

The Shapley Value

The Shapley value is a unique and fair solution to a cooperative game in the characteristic functional form (e.g. Shapley, 1953; Young, 1994). The Shapley value is defined only when the players' benefits can be measured and transferred (within the framework of TU games). In contrast to the nucleolus solution, the Shapley value does not depend on the existence of the core and can therefore also be calculated in the case of a cooperative game with an empty core (Loehman et al, 1979; Young, 1994).

The Shapley value allocation, $\vartheta(x_i)$, to each player *i* is the weighted average contribution to all possible coalitions and sequences:

$$(32) \qquad \vartheta(x_i) = \sum_{S \subseteq N-i} \frac{|S|!(|N-S|-1)!}{|N|!} [v(S+i) - v(S)]$$

Substituting the values of the characteristic function (see Table 7) in equation (32) yields the following allocation solution: $\vartheta(x_i^*) = (1.72, 1.27, 0.17, 0.22)$.

In the current study, the Shapley value fulfils all of the core equations (see Table 7) and therefore possesses the desirable characteristics of the core (individual rationality, group rationality and efficiency). In addition, the Shapley value solutions are (a) linear, splitting the game into several games will not affect the value of the game; (b) anonymous, symmetrical players gain the same allocation; (c) combining dummy players into the regional game will not affect the solution; and (d) efficient, the sum of the players' allocations is equal to the value of the coalition, and is independent of the existence of the core.

[17] In our study the Kernel and Nucleolus solutions coincide.

Discussion

In Table 8 we summarize the results obtained under the different allocation approaches.

Table 8: Allocations of additional net benefits based on game theory principles (in million $)

Player	The nucleolus solution	Percentage of the total net benefit	The Shapley value	Percentage of the total net benefit
1	1.74	51.60%	1.72	50.90%
2	1.24	36.68%	1.27	37.56%
3	0.18	5.30%	0.17	4.96%
4	0.22	6.42%	0.22	6.58%

The solutions obtained from the different approaches can be evaluated in terms of efficiency, fairness and acceptability to the players. The values of the characteristic function were achieved by the optimal values of the relevant objective functions of the CP's Planning Model. These procedures guarantee the efficiency of the allocation solutions presented in this section which include participants' compensations via side payments. In addition, no surplus is left. In the current study, the examined solutions satisfy all of the core equations (see Table 7) and therefore possess its desirable characteristics

The city gains the lion share of the additional net profit allotment (Table 8; more than 50%) under the different approaches examined. This reflects the fact that the city has the highest negotiation strength, being the only wastewater producer in the examined region. The RA gains the second largest additional net profit allotment (Table 8; about a third). The RA's double role in the examined region, as the largest tertiary wastewater consumer and as a tertiary wastewater supplier to the farmers, provides it with relatively high negotiation strength compared to the other wastewater consumers (nearby and distant farmers). The nearby and distant farmers serve only as wastewater consumers in the region. At first, the farmers' allocations of the additional net profits appear relatively small next to the city and RA allotments. However, comparing the solutions obtained to their initial status (see column 2 in Table 4) shows that the nearby and distant farmers improve their profits by 40 and 35.5%, respectively.

4. Summary and Conclusions

The paper presents a regional level, short-run Planning Model which determines the optimal crop mix and the optimal allocation of the limited (fresh and recycled) water and land resources among all potential users, under certain conditions. The model's objective is to maximize the regional social welfare, composed of the sum of agricultural and environmental net benefits under several agri-environmental restrictions. Given the results obtained from the Planning Model, we analyzed and compared a few allocation methods among the examined parties via an agreed-upon objective middleman whose recommendations are based on different approaches from the concept of TU games. The different approaches refer to the allocation of the additional net benefit (gross benefit minus the parties' stand-alone values) obtained in the examined area, among the parties. The analysis is applied to the Sharon region in central Israel.

The empirical analysis focuses on the monetary incentive for cooperation between the producer of the recycled wastewater, the city, and some or all of the wastewater consumers. It is shown that acting alone is not a desirable solution. Under the grand coalition, the highest additional net profit is achieved and therefore will be preferred by a benevolent central planner.Moreover, the optimal cooperative solution enables each group of farmers to reallocate their freshwater quota efficiently, to cultivate new land areas without uprooting orchards and to expand the area planted for crops which can be irrigated only with fresh water or with wastewater purified to a tertiary level. In addition, the use of tertiary wastewater by the farmers reduces the amount of irrigation with fresh water by 1.1 M^3, compared to the non-cooperative scheme.

Although the proposed solution (i.e. a grand coalition) is economically efficient, it may be rejected by one or more of the economic entities in the region unless an acceptable allocation scheme is mutually agreed upon. Since the quota of fresh water is not transferable by law in Israel, the only way to affect the distribution of the regional additional net benefit from cooperation is through direct monetary transfer (side payments). We examined and compared different allocation schemes based on commonly used concepts from the game theory literature, i.e. the Core, the Shapley values and the Nucleolus. Being the only wastewater producer in the region, the city has the highest negotiation strength. Therefore, under all examined approaches, the city gains the highest additional net profit allotment (more than 50% of the total). The RA gains the second largest additional net profit allotment (about a third). The RA's double role in the examined region, as the largest tertiary wastewater consumer and as a tertiary wastewater supplier to the farmers, provides it with relatively high negotiation strength. The two groups of farmers gain the lowest allotment, being only wastewater consumers. However, when comparing the solutions obtained to their initial status, we find that the nearby and distant farmers improve their profits by 40 and 35.5%, respectively.

All of the suggested solutions are reasonable and fair and are expected to be accepted by all the players without distorting the efficiency. Moreover, all of the suggested solutions fulfil the core equations and therefore possess the desirable characteristics of the core (individual rationality, group rationality and efficiency). It is also expected that the suggested solutions will receive the approval of the "green" lobbies, due to the significant contribution to the environment (i.e. river rehabilitation) and to better utilization of the scarce freshwater resource.

Finally, regional analyses under uncertain conditions have to be performed in order to provide a sound basis for policy decisions. The models presented in this research can serve as a building block for such extended analyses.

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APPENDIX I

A. *Calculation of* p_n^{ij}

p_n^{ij} is given by

(1.1) $$p_n^{ij} = (\hat{p}_n - e_n^i) \cdot y_{ng}^{ij} - p^d \left(\bar{k}_n - k^j w_{ng}^{ij}\right) - F_{ng}^i$$

where:

$\hat{p}_n$ denotes the price at the farmer's gate of crop *n* (\$/kg);

e_n^i is the variable costs (\$/kg) of crop *n*, which depend on the level of crop production, not including the cost of water;

y_{ng}^{ij} is the yields (kg/ha) of crop *n* grown by the *i*th farmer irrigated with water from source *j* and located in *g* (for a more detailed calculation of y_{ng}^{ij}, see subsection B below);

p^d is the price of one unit of nitrogen fertilizer (\$/kg);

$\bar{k}_n$ is the recommended level (kg) of nitrogen for 1 ha of crop *n*;

k^j is the amount of nitrogen (kg) in water from source *j*;

F_{ng}^i is the fixed cost per ha from crop *n* located in *g*, which does not depend on crop yields, such as infrastructures;

w_{ng}^{ij} is the annual amount of water required for irrigating 1 ha of crop *n* located in *g* by farmer *i*. We assume that the amount of w_{ng}^{ij} is predetermined via commonly used best-management agricultural practices

B. *Calculation of* y_{ng}^{ij}

y_{ng}^{ij} is given by

(1.2) $$y_{ng}^{ij} = \bar{y}_{ng}^i - \bar{y}_{ng}^i \cdot \frac{L_{ng}^j}{100}$$

where:

$\bar{y}_{ng}^i$ is the maximum yield (kg) of crop *n* located in *g* in the absence of salinity stress;

L_{ng}^j is the yield loss function of crop n irrigated with water from source *j* and located in plot *g*.

We adopt the specification of the yield loss function which suggests that below a given soil salinity threshold, the yield of a crop is not affected, while above this threshold, the yield decreases linearly with soil salinity (Mass and Hoffman, 1977). Formally, the yield loss function can be stated as follows:

$$L_{ng}^j = \begin{cases} \gamma_n + \delta_n \cdot S_{ng}^j & if \;\; T_{ng}^j > Soil\ salinity\ threshold\ of\ crop\ n \\ 0 & if \;\; T_{ng}^j \leq Soil\ salinity\ threshold\ of\ crop\ n \end{cases}$$

To incorporate L_{ng}^{j} in the Planning Model, we rewrite it as

$L_{ng}^{j} \geq \gamma_n + \delta_n \cdot T_{ng}^{j}$ *or* $0 \geq -L_{ng}^{j} + \gamma_n + \delta_n \cdot T_{ng}^{j}$

where:

γ_n, δ_n are crop-related parameters that should be estimated via field experiments (e.g. Mass and Hoffman, 1977).

The average electrical conductivity in the soil (ds/m), T_{ng}^{j}, planted for crop *n* which is irrigated with water from source *j* and is located in plot *g* is

(1.3) $T_{ng}^{j} = 0.5(T_{ng}^{1j} + T_g^0)$

In other words, T_{ng}^{j} is the average of the electrical conductivity in the soil in the root zone located in *g* between its level at the beginning of the irrigation season, T_g^0, and its level at the end of the season (after irrigating crop *n* with water from source *j*), T_{ng}^{1j}. T_g^0 is exogenously determined and T_{ng}^{1j} is obtained from the following equation:

(1.4) $T_{ng}^{1j} = T_g^0 \cdot \frac{A_{ng}^{j}}{B_{ng}^{j}} + \frac{D^j w_{ng}^{j}}{B_{ng}^{j}}$, $A_{ng}^{j} \equiv V_g - 0.5\beta_g \left(w_{ng}^{j} + \tau\right)$, $B_{ng}^{j} \equiv V_g + 0.5\beta_g \left(w_{ng}^{j} + \tau\right)$,

where:

V_g is the average amount of water (m^3/ha) contained in the root zone of soil plot *g*;
β_g is the fraction of applied irrigation water leached out the root zone of plot *g*;
τ is the annual average amount of rain during the growing season (m^3);
D^j the electrical conductivity (ds/m) of water from source *j*.

Since we are dealing with a maximization model, we get from (1.3) that the level of L_{ng}^{j} at the optimal solution will be equal to: $\max\{0,\ \gamma_n + \delta_n \cdot S_{ng}^{j}\}$. In addition, $0 < L_{ng}^{j} \leq 100$.

APPENDIX II
Implementing the Shapley-Bondareva theorem

Definition: Coalitions $S_1,...,S_k$ and the non-negatives numbers $\delta_1,...,\delta_k$ are balanced collections with balanced weights, if for each player *i* there exists

$$\sum_{m/i\in S_m}\delta_m = 1, \qquad \forall i\in N$$

The collection of coalitions $S_1,...,S_k$ is the minimal balanced collection with balanced weights $\delta_1,...,\delta_k$ if its entire subgroup is not balanced.

The cooperative game with the characteristic function *v* has a non-empty core if and only if, for all minimal balanced collections, $S_1,...,S_k$, with a unique balanced weights vector $\delta=(\delta_1,...,\delta_k)$, satisfies

$$\sum_{m=1}^{k}\delta_m v(S_m)\le v(N)$$

Table 1.1 presents the minimal balanced collections and the balanced weights which are relevant to our research.

Table 1.1: Balanced collections and weights of the regional game

No.	**Minimal collections**	**Balanced weights**
a	[(4),(3),(2),(1)]	1, 1, 1, 1
b	[(4),(3),(1,2)]	1, 1, 1
c	[(4),(2),(1,3)]	1, 1, 1
d	[(3),(2),(1,4)]	1, 1, 1
e	[(4),(1,2,3)]	1, 1
f	[(3),(1,2,4)]	1, 1
g	[(2),(1,3,4)]	1, 1
h	[(4),(3),(1,2,4),(1,2,3)]	1/2, 1/2, 1/2, 1/2
i	[(4),(2),(1,3,4),(1,2,3)]	1/2, 1/2, 1/2, 1/2
j	[(3),(2),(1,3,4),(1,2,4)]	1/2, 1/2, 1/2, 1/2
k	[(4),(3),(1,2,4),(1,2,3),(1,2)]	2/3, 2/3, 1/3, 1/3, 1/3
l	[(4),(2),(1,2,3),(1,3,4),(1,3)]	2/3, 2/3, 1/3, 1/3, 1/3
m	[(3),(2),(1,3,4),(1,2,4),(1,4)]	2/3, 2/3, 1/3, 1/3, 1/3
n	[(4),(3),(2),(1,4),(1,3),(1,2)]	2/3, 2/3, 2/3, 1/3, 1/3, 1/3

When calculating the balanced weights, we use the core equations (Table 7), for example for the minimal collection m:

From v, vi, vii and ix, x, xi (Table 7),

$$x_1+x_2+x_1+x_3+x_1+x_4+x_2+x_3+x_4\ge v(1,2)+v(1,3)+v(1,4)+v(2)+v(3)+v(4)$$

Remember that $x_2\ge v(2)$, $x_3\ge v(3)$ and $x_4\ge v(4)$. The last four expressions and *i* imply

$$3v(1,2,3,4) \geq v(1,2) + v(1,3) + v(1,4) + 2v(2) + 2v(3) + 2v(4)$$

Or,

$$v(1,2,3,4) \geq 1/3[v(1,2) + v(1,3) + v(1,4) + 2v(2) + 2v(3) + 2v(4)]$$

It can easily be shown that all the minimal collections (a-m) satisfy $\sum_{m=1}^{k} \delta_m v(S_m) \leq v(N)$, and therefore **the regional game in our research has a non-empty core**.

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