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Control of Nitrates Pollution Using Multi-Objective Decision Analysis Technique

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Abstract: Nitrogen is essential to all life and most crop plants require large quantities to sustain high yields. The formation of nitrates is an integral part of the nitrogen cycle in our environment. Unfortunately, nitrate can be leached from the rooting part of the soil or through the subsurface drain effluent and cause environmental problems such as eutrophication and health hazard. Control of fertilizer applications (dose &frequency), along with proper design of subsurface drainage system (depth and spacing), is key factors in minimizing risks of nitrate pollution in drains and groundwater. Moreover, higher fertilizer efficiency is expected to prevail. Building capacities and raising awareness of farmers towards nitrates pollution problems (causes, precautions and remedies) are critical elements for the success of pollution abatement programs at large. A management system is developed to assist the decision maker in selecting among many alternatives, the most suitable solution for the problem of drainage and ground pollution with nitrate using Multi - Objective Decision Analysis Technique (MODAT). This system was formulated in a user-friendly computer application named Drainage Ground Water Pollution with Nitrate (DGWPN). Different evaluation criteria are suggested and checked by agricultural and drainage specialists where a weight is assigned to each evaluation criterion based on their experience. Also, to calculate criterion score for each solution, improvement percentage is used. The weighted summation method is used to rank the suggested solutions and choose the best one. The system is tested in Zankalon Experimental Station (ZES) in Egypt. The study revealed that the developed decision support system could assist the decision-maker in selecting the best solution of the problem of drainage and groundwater pollution with nitrates. Moreover, using controlled drainage for rice cultivation with split ammonium sulphate in two doses is the best practical solution as it reduces the nitrates leached to drainage water, decreases the nitrate leached into groundwater and increases the fertilizer efficiency.

Key words: Nitrates · Multi-objective · Decision · Subsurface · Drainage · System

INTRODUCTION

Agriculture drainage systems are normally designed to control the twin problems of waterlogging and salinization. Meanwhile, the basic objective is to provide a root zone environment that facilitates plant growth and optimizes crop production. Water quality is a factor closely related to drainage of agricultural croplands. Pollutants that attach to soil particles can be transported with drainage effluent and pollutants that stay in solution are often transported through the drainage system to receiving water bodies such as river and lakes.

Nitrate will eventually percolate to groundwater or return drainage system to receiving water bodies such as river and lakes. Nitrate will eventually percolate to groundwater or return to surface streams via subsurface drainage systems. The presence of increased nitrate levels in aquatic ecosystems promotes increased oxygen consumption, eventual eutrophication and may render the water unfit for drinking. The problem of fertilizer abuse, drainage and groundwater pollution with nitrate fertilizer can be solved by addressing the grassroots, i.e., to irrigate through precise calculation of irrigation quantity and efficiency, to control the amount of fertilizer addition

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and control the drainage water from agriculture land as it carries the pollutants to ground water. Fertilizer control includes fertilizer application frequency (scheduling) and its dose. In this study the solution of applying more than one dose in small quantity was considered since this is accepted to reduce the concentration of nitrate in drainage and ground water and to increase the fertilizer efficiency. The objective of this research is to develop a management system for irrigation, drainage and fertilizer to maximize fertilizer efficiency and minimize pollution of drainage and groundwater with nitrate for rice cultivation.

Multi-Objective Decision Analyses Techniques: A multi-objective evaluation technique assists the decision maker in selecting among a finite number of alternatives solutions according to their preferences. The formulation of the problem and solution by a multi-objective evaluation technique can be described as follows, Refer simply to the reference number, as in [1].

- A general objective related to the problem must be made.
- A set of feasible alternatives solutions must be specified.
- A set of relevant criteria for evaluation must be specified.
- A preference for each criterion must be given by the decision-maker
- An evaluation technique should then be used.

The feasible set of alternatives X= {x_1, $x_{2,\,,\,x\ j}$, $x_{\ n}$) and the set of relevant criteria Y={ y_1, y_2, …, y_i, ..y_m} is always described by a payoff or impact matrix R. The rating of the i th criterion on the j th alternative (I=1, 2, .. m and j = 1, 2, .. , n) is represented by r_{ij}.

$$\text{Criteria} \ldots \quad R \quad \begin{vmatrix} r_{11} & r_{12} & r_{1n} \\ r_{21} & r_{22} & r_{2n} \\ \ldots & \ldots = & \\ r_{m1} & r_{m2} & r_{mn} \end{vmatrix}$$

A weighting vector W always describes a preference of each criterion. The rating of the I th. criterion represents the relative importance of criterion I compared to the other criteria.

$$W = \begin{vmatrix} W_1 \\ W_2 \\ W_m \end{vmatrix}$$

Alternative Solutions: The solution of drainage and groundwater pollution with nitrate are believed to be achieved through controlling the amount of fertilizer addition and/or controlling the drainage water from agriculture land as it carries the pollutants to groundwater. This can be done through several mechanisms as follows:

Controlled Drainage (CD): The objective of controlled drainage is to maintain an elevated water table during the growing season, by restricting drain flow. Higher water table increases the rate of de-nitrification (i.e formation of gaseous forms of nitrogen by biological reduction of nitrite and nitrate) and enhances the use of nutrients by plants. This system could also be a beneficial practice for reducing nitrate losses in outflow on selected crops refer simply to the reference number, as in [2].

Wider Drain Spacing (WS): The Egyptian Public Authority for Drainage Project (EPADP) uses the steady state equation of Hooghoudt in the design of lateral drains,

$$S^2 = \frac{8kdh + 4kh^2}{q} \qquad (1)$$

where,

S : Drain spacing (m)
h : Hydraulic head above drain level at midway between drains (m)
q : Drainage coefficient (m/day)
k : Soil saturated hydraulic conductivity (m/day)
d : Equivalent depth of the impermeable layer below the drains (m)

From this equation, it is obvious that if the drain spacing increases the drain discharge will decreases. Reference [3] was the first one found that increasing drain spacing from 20 to 40 m reduced predicted NO_3 - N losses by over 40%.

Fertilizer Control (FC): Fertilizer control includes fertilizer application dates and fertilizer dose. The time of fertilizer application is very important; fertilizer is to be applied as close as possible to the time when the crop takes up nitrogen. Fertilizer dose and split applications are more likely to apply nitrogen to the soil when the plant needs it Refer simply to the reference number, as in [4]. To reduce negative effect of fertilizer (pollution), it is better to use more than one dose in small quantity Refer simply to the reference number, as in [5].

Preventive Measures (Environmental Laws EL): Charges and subsidies are effective incentives to encourage people to perform certain activities, or to discourage them from doing so. In Egypt, as each farmer posses a small plot of cultivated land, one lateral can serve many plots and measuring of pollutants in the manhole is not a logical solution. To apply charges or laws, measurements can be done through observation well, installed in the middle of each field.

Remedial Measures (Water Protection Association WPA): Water pollution is an important subject as it is related to many agencies; agriculture, irrigation, drainage, environment and health. These different agencies have to form one committee (Water Protection Association) to solve the existing problem of water pollution. In addition to all the pervious agencies and before them is the farmer role. Lack of farmer awareness is the main reason of the water pollution. Farmer awareness is a corner stone in the protection of drainage and groundwater from pollution as it builds the connection between the specified agencies and the water user.

Objective Analysis and Criteria Generation: The objectives of this research are of two folds Socio-economic, such as increase farm income, protect human health and build farmer awareness and Environmental objectives such as protection of water from nitrate pollution and conservation of water resources. Thus, the cost and fertilizer efficiency will be taken as a criterion of Economic objective, health hazard and farmer awareness as a criterion of Sociological - objective. Irrigation quantity, leaching nitrate to drainage water and groundwater will be taken as a criterion for Environmental objective.

In this study the weighing vector has the following sequence Refer simply to the reference number, as in [6].

- Leaching of nitrate - nitrogen to drainage water (W1)
- Leaching of nitrate – nitrogen to groundwater (W2)
- Fertilizer efficiency (W3)
- Farmer awareness (W4)
- Irrigation quantity (W5)
- Health hazard (W6)
- Total cost of each solution (W7)

The weighting vector is filled with numbers, which describe the weight of each criterion. To get numbers describing the weight of each criterion, a simple expert system was applied. Twenty drainage and agricultural specialists are requested to put a weight for each criterion, as they believe using a seven- point scale. Nine specialists only from Soil &Water and Environmental Research Institute (SWERI) of the Agricultural Research Center (ARC) and Drainage Research Institute (DRI) of the National Water Research Center (NWRC) responded to this study. The results of their opinions are shown in Table (1).

It is noticed that there are variations between the specialist's weights for each criterion; therefore normalizing the weight values was done using the following equation,

$$\text{Normalized value} = \frac{Criterion \cdot weight}{Maximum \cdot criterion \cdot weight} \tag{2}$$

The results of the normalized values are taken. The summation of each normalized value for each criterion was calculated and ranking of their priorities was done according to the summed values. Ranking of the evaluation criteria is then found from table (2) where leaching of nitrate to drainage water having the higher weight, while total cost having the lower weight. The result may differ in case of higher responded number of specialist.

Evaluation of Alternative Solutions: The alternative solutions were evaluated using the Weighted Summation Method (WSM). This method is probably the easiest and most commonly used technique for the comparative evaluation of alternatives. The basic component of WSM is called "simple multi- attribute procedures." The utility of each alternative U1 is determined by the summation of the weighted numerical values of each criterion. The alternative, which has the greatest utility, is the best alternative solution.

$$Uj = \sum_{i=1}^{m} W_i \cdot S_{ij} \tag{3}$$

$$U_{optimal} = \max . U_j \tag{4}$$

for all j

Where sij is the standardized value of rij.

The standardization method used, when the higher is the better:

$$\text{Standardized score} = \frac{score \cdot - \min \cdot raw \cdot score}{\max \cdot raw \cdot score \cdot - \min \cdot raw \cdot score}$$

Table 1: Specialists Weights for Different Criteria

Exp. N o.	N_{dw}	N_{gw}	IQ	Neff.	HH	Total Cost	FA
Exp.1	7	7	5	2	1	1	4
Exp.2	7	7	4	1	1	1	3
Exp.3	7	7	1	7	5	2	4
Exp.4	6.5	4	3	6.5	4	4	4
Exp.5	6	1	1	4	5	5	4
Exp.6	7	4	4	7	7	3	6
Exp.7	7	7	4	7	7	1	5
Exp.8	6	7	5	6	7	4	5
Exp.9	7	5	2	3	4	4	2
Sum	60.5	49	29	43.5	41	25	37

Ndw: leaching of nitrate-nitrogen to drainage water
Ngw: leaching of nitrate – nitrogen into ground water
Neff: Fertilizer efficiency
FA: Farmer Awareness
IQ: Irrigation quantity
HH: Health Hazard
Total Cost: Cost of alternative solution

Table 2: Normalized Weights for Different Criteria

Exp. N o.	N_{dw}	N_{gw}	IQ	Neff.	HH	Total Cost	FA
Exp.1	1	1	1	0.286	0.143	0.2	0.667
Exp.2	1	1	0.8	0.143	0.143	0.2	0.5
Exp.3	1	1	0.2	1	0.714	0.4	0.667
Exp.4	0.929	0.571	0.6	0.929	0.571	0.8	0.667
Exp.5	0.857	0.143	0.2	0.571	0.714	1	0.667
Exp.6	1	0.571	0.8	1	1	0.6	1
Exp.7	1	1	0.8	1	1	0.2	0.833
Exp.8	0.857	1	1	0.857	1	0.8	0.833
Exp.9	1	0.714	0.4	0.429	0.571	0.8	0.333
Sum	8.6	7	5.8	6.2	5.9	5	6.2
Weight	7	6	3	5	4	2	5

And when the lower is the better:

$$\text{Standardized score} = \frac{\max \cdot raw \cdot score \cdot -score}{\max .raw.score - \min .raw.score}$$

This standardization method yields results where the highest level is equal to 1 and the lowest level is equal to 0. These scores describe the impact of each solution on each criterion. Impacts are expressed in the criteria decided upon at an earlier stage. The impact of each solution on different used criteria should be measured after the application of each solution to develop a general decision support system. Therefore, a simple expert system was done, where agricultural and drainage specialists were requested to assume the percentage of improvement in each criterion after the application of each suggested solution based on their experience Table (3). These improvements were used to predict the criterion scores.

Table 3: Improvement Percentage of Different Solutions

	Criteria						
Solutions	N_{dw}	N_{gw}	Neff.	FA	IQ	HH	Total Cost
Controlled Drainage	45	10	10	-	30		Calculated
Wider drain spacing	14	10	10	-	5		Calculated
Fertilizer Control	55	15	10		35		Calculated

Table 4: Predicted Scores of Criteria

	Criteria						
Solutions	N_{dw}	N_{gw}	Neff.	FA	IQ	HH	Total Cost
Controlled drainage				-		10	Calculated
Wider drain spacing				-		6	
Controlled fertilizer				8		10	
Water Protection Association	7	7	7	7		8	
Environmental law	5	5	6	5		7	

A scale range from 1 to10 is given as basis for evaluating the impact of different solutions concerning these qualitative criteria Refer simply to the reference number, as in [7]. Levels 10 and 1 represent the higher and lower measurements, respectively. The score of 8 means the favorite impact of solution, while that of 7 and 6 are for more favorable impact, 5 for less favorable impact. The suggested scores for the criteria for the two solutions of water protection associations and the environmental law are given in Table (4). Farmer awareness and health hazard scores for the first three solutions are also given in Table (4).

Testing Developed System in ZES: The developed system was tested in a representative case study in (ZES) to evaluate the impact of different solutions on the selected set of criteria. ZES is located at 84 km north east of Cairo, Sharkia Governorate, Egypt. The experimental station has a total area of about nine feddans. The soil of the experimental station is classified as clay soil. The hydraulic conductivity was measured in 2.0 m deep holes using the auger hole method Refer simply to the reference number, as in [8]. The average soil hydraulic conductivity is 0.05 m/day and the average soil bulk density is1.32 g/cm^3.

To fulfill the study objective two experiments were carried out in Zankalon Experimental Station (Figure 1). In the first experiment; three units (1, 2 and 3) were taken. Unit 1 represents the conventional drainage system of 20 m drain spacing and 1.20 m drain depth, while unit 2 represents controlled drainage system of 20 m drain spacing and 0.6 m drain depth and unit 3 represents drainage with wider spacing of 40 m and 1.20 m. For unit 3 it is obvious that drain spacing of 40 m was used twice

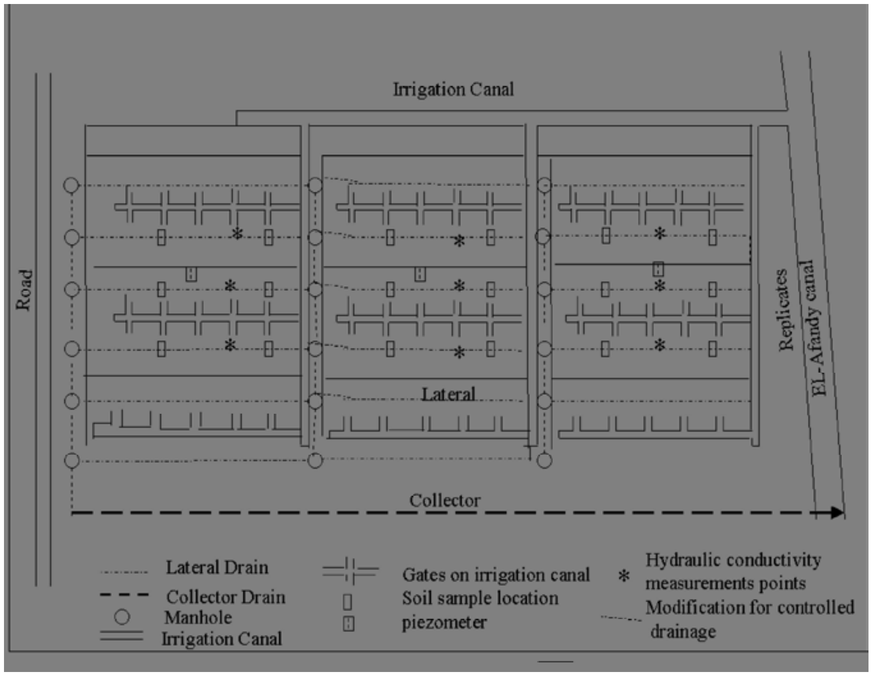

Fig. 1: Schematic Diagram of Zankalon Experimental Station

that of unit (1) or unit (2) because of the limited area and the difficulty of reconstruction of drainage system. Moreover, for unit 3 one lateral was blocked to obtain new spacing 40 m between the laterals. In the second experiment, two units (1-2) were considered. Unit 1 represents the conventional drainage system of 20 m drain spacing and 1.20 m drain depth, while unit 2 represents controlled drainage system of 20 m drain spacing and 0.6 m drain depth.

Fertilizers Applications: Two alternative types of nitrogen fertilizer were used for rice cultivation in the two experiments. Urea fertilizer (46% N) was added once after four weeks from transplanting date with a rate of 100 kg/fed for experiment (1). For experiment (2) Phosphate and nitrogen fertilizers were added as follows: Super Phosphate (15 % P_2O_5) was added during land preparation for planting with a rate of 100 kg/fed. Ammonium Sulphate fertilizer (20.5% N) was added in two doses during the growth season. The first dose was 100 kg/fed added after four weeks from transplanting date, while the second dose was added at a rate of 50 kg/fed after two weeks from the first application.

A field-monitoring and sampling program was followed in ZES. The monitoring program includes measuring irrigation and drainage water quantity while the sampling program includes taking samples from drainage water, groundwater, soil and plants for nitrate chemical analysis in Drainage Research Institute (DRI) laboratory. Table (5) shows nitrate analysis of different units in Zankalon.

Predicted Scores of Criteria's Set: To calculate the predicted score of different criteria after application of each solution, each criterion is calculated as follows:

Predicted Score of Leached Amounts of Nitrate -Nitrogen to Drainage Water

To calculate the predicted leaching nitrate - nitrogen to drainage water after application of each solution, the leaching nitrate to drainage water with conventional drainage system is calculated as follows,

$$(\text{Nitrate})dwi = (\text{Nitrate})dwcd * (100 - xi\%) \quad (7)$$

where:
(Nitrate) dwcd: leaching Nitrate to drainage water of conventional drainage

$$\text{Leached nitrogen in drainage water} = \frac{86.4q * (NO3 - N) Concentration.ion}{A} \quad (8)$$

Predicted Score of Leaching Amounts of Nitrate – Nitrogen into Groundwater

Table 5: Nitrate Analysis in Zankalon Drainage

Units	Fertilizer type and dose	Leaching nitrate (kg/fed.) N_{dw}	N_{gw}
Controlled drainage	Urea100 kg/fed.	1.374	16.586
Wider drain spacing	Urea100 kg/fed.	2.17	15.79
Controlled drainage and fertilizer	AmmoniumSulphate150 kg/fed.	1.25	3.84

The predicted leaching Nitrate into ground water after application of each solution is as follow;

Predicted (Nitrate) gwi = (Nitrate) gwcd *(100 –x i%) (9)

where:
Predicted (Nitrate) gwi: Predicted leaching Nitrate into groundwater
(Nitrate) gwcd: Leaching Nitrate into ground water for conventional drainage system

$$J_C = q_g * c_g \quad (10)$$

where:
qg : volume of water flow to groundwater
Cg : mass of solute per a unit volume of solution.
Jc : is given in terms of mass of solute passing through a unit cross-section area of a soil body per unit time.

Predicted Score of N Efficiency: The predicted efficiency of nitrogen fertilizer after the application of each solution is calculated as follows:

Predicted (Neff.) i = N eff.cd* (100 + xi %) (11)

where:
qg : volume of water flow to groundwater
Cg : mass of solute per a unit volume of solution.
Jc : is given in terms of mass of solute passing through a unit cross-section area of a soil body per unit time.
N eff. cd : Is the efficiency of conventional drainage system

$$\text{Neff.cd:}=\frac{N_{uptake} - N_s}{N_{rec.app.}} \quad (12)$$

Nuptake : Nitrate uptake by plant
Ns : the nitrate uptake by plant from the soil without addition of fertilizer
Nrec. app. : the recommended nitrogen fertilizer applied.

Predicted Score of Irrigation Quantity: The predicted irrigation quantity after application of each solution is calculated as follows,

Predicted (IQ)i = (IQ)CD*(100-xi%) (13)

where:
(IQ)i : predicted irrigation quantity
(IQ)CD : Irrigation quantity for conventional drainage system.

where:
(IQ)i : predicted irrigation quantity
(IQ)CD : irrigation quantity for conventional drainage system.

$$\text{(IQ)CD} = \left(\frac{ET}{1-LR}\right)/A_s \quad (14)$$

ET : crop consumptive use evapo-transpiration (mm)
As : Study area
LR : leaching requirement

Total Cost: The total cost of each alternative solution is calculated as follows;

Total Cost = Agriculture Cost + Drainage Cost + Awareness Cost or Environmental law Cost (15)

Health Hazard: With respect to chronic effects, JECFA Institute recently re-evaluated the health effects of nitrate/nitrite, confirming the pervious ADI of 0-3.7 mg/kg of body weight per day for nitrate ion and establishing an ADI of 0-0.06 mg/kg of body weight per day for nitrite ion Refer simply to the reference number, as in [8]. Because of the possibility of the simultaneous occurrence of nitrite and nitrate in drinking water, the sum of the ratios of concentrations of each to its guideline value (GV) should not exceed one Refer simply to the reference number, as in [9]. i.e.:

$$\frac{C_{nitrite}}{GV_{nitrite}} + \frac{C_{nitrate}}{GV_{nitrate}} \le 1 \quad (16)$$

where:
C : concentration of nitrite or nitrate
GV : guideline value of nitrite or nitrate

Blood samples analysis is required to apply equation 16, which is out of the scope of this work. A qualitative predicted score is used.

Farmer Awareness (FA): In order to convince farmers; appropriate information should be transferred to them via technically qualified professionals.

The following equation can be used;

$$FA = \frac{No.of \cdot aware \cdot farmers \cdot sample}{Total \cdot No.of \cdot farmers \cdot sample} \quad (17)$$

RESULTS

Calculation steps of the multi – objective decision analysis using Weighted Summation Method are presented in tables (6-8). Table (6) shows the impact matrix, which is filled with the calculated and assumed scores.

Table (7) shows the standardized matrix, which is filled with the scores after the standardization process.

Table (8) shows the evaluation matrix or appraisal matrix, which is filled with the results of multiplying weight and the standardized scores. It could be seen from the evaluation matrix and Fig. (2) that ranking of the suggested solutions is as follows;

Table 6: Impact Matrix

Criteria	CD	WS	CF	EL	WP
Ndw	1.36	2.12	0.97	5.00	7.00
Ngw	19.07	19.07	5.05	5.00	7.00
Neff.	31.50	31.50	61.00	6.00	7.00
FA	-	-	8.00	5.00	7.00
IQ	2173.85	2950.22	2503.60		8.00
HH	10.000	6.00	10.00	7.00	8.00
Total Cost	1225.05	1203.05	1217.95	3000.0	4000

Table 7: Standardized Matrix

Criteria	CD	WS	CF	EL	WP
Ndw	0.935	0.808	1.000	0.332	0.000
Ngw	0.000	0.000	0.996	1.000	0.858
Neff.	0.464	0.464	1.000	0.000	0.018
FA	-	-	1.000	0.000	0.667
IQ	0.264	0.000	0.152	1.003	1.000
HH	1.000	0.000	1.000	0.250	0.500
Total Cost	0.992	1.000	0.995	0.358	0.000

Table 8: Appraisal Matrix

CD	WS	CF	EL	WP
6.547	5.657	7.000	2.322	0.000
0.000	0.000	5.979	6.000	5.147
2.318	2.318	5.000	0.000	0.091
-	-	5.000	0.000	3.333
0.792	0.000	0.455	3.008	3.000
4.000	0.000	4.000	1.000	2.000
1.984	2.000	1.989	0.715	0.000
15.641	9.975	29.423	13.045	13.571

- Controlled fertilizer & Controlled drainage
- Controlled drainage
- Water Protection Association
- Environmental law
- Wider drain spacing

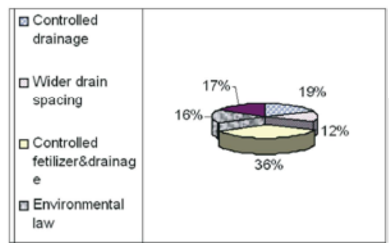

Fig. 2: Ranking of Solutions

CONCLUSIONS

Based on the study results; the following could be concluded:

- The developed decision support system DGWPN in this study can assist the decision-maker in selecting the best solution of the problem of drainage and groundwater pollution with nitrate for the study area.
- The controlled fertilizer and controlled drainage is preferable solution for the problem of drainage and ground water pollution with nitrate.

Recommendations:

- Series of field studies have to be conducted to determine effects of drain depth, drain spacing, nitrogen fertilizer type and Nitrate losses from drained agricultural lands and these studied should be constructed to represent a broad range of soils and crops.
- Effective governance based on the cooperation between agriculture and drainage authorities is essential for achieving integrated irrigation / fertilizer management.

- Awareness program for farmers should be enhanced through specialists in fields of irrigation, drainage, environment, agriculture and health.

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