17 - PERFORMANCE OF IRRIGATION CANALS AND WATER DISTRIBUTION MODELLING

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Abstract: This paper proposes an evaluation of current irrigation water distribution systems and shows ways on how to improve existing approaches through modelling. This work describes water distribution mathematical methods, subjected to technical conditions of irrigation systems, cropping patterns and applied irrigation technique. A solution for the problem of operational water losses in canals, subjected to optional location of irrigated areas along the canal, is described. The irrigation system is formalized as a directed graph on a multivariable network, and a number of optimization problems are formulated so that they occur at various stages of the water distribution process. Different types of uncertainty resident in these processes are considered and various criteria are studied as to allow the quantitative assessment of different water distribution options. Besides, this paper formulates an optimal control problem that links crop irrigation schedules with an actual water management situation. It proposes a solution for these problems in the experimental farm "Azizbek" in Akhunbabayev district, Fergana province.

Keywords: Irrigation system, Canal control, Canal operation and management, Water distribution, Optimization.

Introduction

Even in the Soviet period, with large irrigated farms, like collective and state farms, with large fields (8-15 ha) and brigade's rotation areas (50 to 150 ha), water delivery and distribution to water users based on crop water requirements were very complicated. These tasks were mainly solved by providing continuous flow to brigades, or through strictly fixed water rotation among them. The brigades would then distribute water between fields in a certain

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obligatory order of priority in order to avoid tail runoff from the field. This was performed under responsibility of brigade-leaders, and for outside eyes this process seemed to be a 'black box' of brigade operations. Nowadays, given the transition to a market economy, those tasks have become more complicated for a number of reasons. Water demands of some farm fields became much higher – farmers wanted to receive water when the crops needed it, i.e. closer to the water consumption schedule. Taking into account the difference in the fields soil conditions, and thus, shifts in the required irrigation dates, one may determine the so called under-estimated irrigation water demand along the minor distributor canal. This demand is then linked with the potential "top-down" water supply among the irrigation network's hierarchical levels and the water supply order, which is established in one or another system. Thus, the task of water supply and distribution at the lower level (up to field) of irrigation network is divided into the following:

1. Demand estimation of separate fields along the canal, based on water requirements/consumption simulated by the SEDAM model and the ISAREG – SADREG models (as reported by Gonçalves *et al.*, 2005a, 2005b; Fortes *et al.*, 2005);

2. Obtain information on the canal's planned and expected water supply or on water distribution order, which is established by a Water User Association or any other agency (like District water management organization), which is also a possible input to SEDAM model;

3. Estimate possible shifts in the average irrigation dates (± n-number of days), by avoiding damage to crops, in order to "complete" the water use schedule, i.e. maximally meet "demand for resource" under minimum land productivity losses and idle discharge, which can be optimized with SEDAM or through another mathematical modelling rather than by routine methods.

It should be noted that practice also suggests other methods such as: when water is not delivered according to demand but is dictated from the top (WUA or water management organization), either by establishing a strict water rotation order (in terms of volume or time), or by proportional water allocation due to the farmers adaptation to the water supply system instead of making demand. Such systems have been practiced in India and Pakistan ("warabandi", "sheikhjeili"), but, evidently, this causes great difficulties for farms. It is more advisable to arrange an order of water distribution, which, to greater extent, meets crop, field, and farm demands. Thus, this paper describes approaches developed through mathematical modelling to such order of water distribution.

At that, noting SEDAM advantages in water use plan definition, a modelling principle is suggested here as alternative, which tries to bind optimal water use with field parameters and restrictions of upstream sources. The future combination of approaches is desirable.

Water distribution control

Characterizing an irrigation system

An irrigation system is a set of hydrostructures arranged in a form of directed network and designed for delivery of the required volume of water, to given points in space and time, in order to irrigate agricultural lands. Water conveyance is performed through the canal systems having different design, while the flow controlling regulators are the set of specific hydrostructures (gates, weirs, etc.). The required water volumes and delivery time intervals are determined on an area and crop basis. The irrigation systems technical characteristics are usually expressed as maximum discharge, length and canal system efficiency.

The main operational characteristics of an irrigation system are as follows (in order of priority):

1. Degree of water provision of irrigated areas;
2. Degree of water delivery equality to water users;
3. Relative system water losses;
4. Relative flow fluctuations in canals.

The first three characteristics reflect the irrigation system's role of the ameliorative system, while the last one represents the operational load in the system.

When considering the irrigation system as a control object, each of the aforementioned characteristics may be transformed into partial criteria, reflecting a certain aspect in the system's functionality. Since the application of different criteria will result in different options of water distribution, the irrigation's system control problem refers to a multicriteria analysis – as assumed in the DSS SEDAM (Gonçalves *et al.*, 2005b), where target uncertainty calls for additional research implementation regarding the significance of one or another characteristic.

The target uncertainty is not the only type of uncertainty in irrigation systems control. The stochastic nature of hydrological flow that forms available water resources and the weather conditions, forming specific water user requirements, give rise to the next type of uncertainty, which is usually called as «natural uncertainty», and hampers the finding of a unique solution and calls for the search of a certain water distribution control strategy as a function of inflow and current weather conditions.

However, there are also other types of "anthropogenic uncertainty" that require an accurate description of existing relationships between various actors in the irrigation system. This mathematically clear formalization of existing rules among actors in water distribution will allow the improvement of these rules and will make them subject to several conditions, thus reducing this type of uncertainty. Under such conditions, the modeller faces an inevitable problem, relating to the choice between the simplification of the model with simultaneous losses in accuracy, and the increased detail of the model. In the first case, a certain distortion in physical and technical components of the system is allowed, so that, during the parameters identification, the prevalent relationships between actors are implicitly determined. The second way is based on the physical processes and the systems technological components detailed description in order to identify the parameters through indirect evaluations, or even by using other analogous systems. The unknown relationships are not considered in this process of identification and are determined during the second stage, where the former or the rules of water distribution are specified for a given point in time. Despite laboriousness of the second method, the model outputs allow both an opportunity to control the system within a wider range of changes in external conditions and the identification of standalone importance socio-economic consequences.

Formal description of irrigation systems

Water distribution formal description among the irrigation system components – canal, off-takes, and irrigation sectors - is based on the law of conservation of water mass for every given time lag. Hydrodynamics uses the term "quasi-stationary approximation", which is admissible if time of relaxation of flow processes in the system is much less than the time-averaging interval. For the main and secondary canals, the period necessary to reach steady-state conditions is not more than two-three hours; therefore, in models with averaging intervals equalling "day" and "10-day", such approximation is quite admissible. For lower hierarchical levels, the stochasticity of routine changes in regimes is very large if some rules are not introduced. Actual flow fluctuations in tertiary and minor canals are visible in Fig. 1, which shows the initial operation regime of a canal C-1.

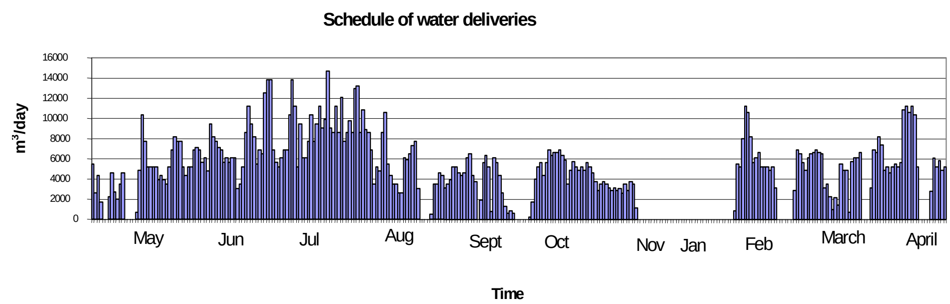

Fig. 1. Actual mode of supply of water at the head of the channel C-1, Fergana province, Azizbek farm.

Let start formulation of the optimal water delivery control and planning problems for irrigation system from considering a terrain limited by a contour $\partial \boldsymbol{g}$, defining an irrigation sector, which is comprised of a set {J} of irrigated areas. Each area produces a certain set of crops $\{R_j\}$, with the following parameters:

$F_{r,j}$, $q^N_{r,j}(t)$, n_j, $j \in \{ J \}$, $r \in \{R_j\}$, $t \in \{T\}$,

where: $F_{r,j}$ is a zone covered by a "r"crop on an area of "j"; $q^N_{r,j}(t)$ is crop function of specific water use by crop "r", subjected to all agronomic and climatic factors; and, η_j is efficiency of j-irrigated area. {T} is control time. A given terrain is covered by a number of irrigation canals diverting water from few sources. Moreover, a share of water is passed as transit.

Let define the directed network as **g**(K,C), where K={0,1, . . .,k} is a set of nodes corresponding to the respective hydrostructures and C={0,1, . . .,c} is a set of arcs identifying canals. Each element $c \in C$ is characterized by a pair of (k,i), such as ($\forall$(k,i), $k \in K$, $i \in K$, $i \neq k$), where "k" is the head node, and "i" is the tail node of a given canal "c". Every canal is characterized by length "L_c" ($L_c \geq x \geq 0$), its efficiency "η_c" and by maximum flow capacity "q_c^{max}". Then, for every canal "c", $c \in \{C\}$, we input a set of offtakes $\{P_c\}$ characterized by a triplet of (p,x,j) , $p \in \{P_c\}$ and $j \in \{J\}$, where "j" is a command area of the offtake "p", and "x" is a coordinate position of the offtake in canal "c". The set of offtakes links the canal network with irrigated areas in a way that one offtake strictly delivers water to the dedicated area, while an irrigated area may be served by several offtakes. A set $\{P\} = \cup_c \{P_c\}$, besides $\{P_c\} \cap \{P_k\} = \varnothing$, $\forall$(c,k), $c \in \{C\}$, $k \in \{C\}$, $c \neq k$. Thus, a set {P} can be considered in form of a set of secondary arcs in an extended directed graph **G**(K,C,P,J), herein after called as «irrigated area graph».

Let consider a single canal having parameters, such as "L", the length, and "η", the efficiency of the canal, which delivers water to a number of offtakes and passes water as transit. Let express discharge in canal at a distance of "x" from its head as q(x,t), while discharge in offtake "p" at the same distance as $q_p(x,t)$. Naturally, the following inequation should be satisfied:

$$q^{max} \geq q(x,t) \geq q_p(x,t), \ \forall\ L \geq x \geq 0, t \in \{T\} \qquad [1]$$

In a given period, the discharge values at the head and tail of the canal are $q\ (0,t)$ and $q\ (L,t)$, respectively. Considering "η" as the main characteristic of water losses in canal along the path "x", the equation for variable discharge is written as:

$$\frac{dq}{dx} = -\lambda \times q\,; \qquad \text{when } L \geq x \geq 0, \lambda > 0; \qquad [2]$$

where λ is the loss intensity in the canal which is to be determined.

By considering λ as a constant for a given canal and integrating equation [2] based on the conditions below at both of the canal:

$q(0,t)= q(0, t)$ and $q(L,t) = \eta \times q(0,t);$ [3]

we obtain the discharge equation in the canal for any section at the distance "*x*" from the upstream end:

$$q(x, t) = q(0, t)\times \mathbf{exp}(\frac{x}{L}\ln\eta\ );\ L, \geq\ x\ \geq 0; \quad [4]$$

The relationship between discharge values in sections x_1 and x_2 is derived from equation [4]:

$$q(x_2, t) = q(x_1, t)\times \mathbf{exp}(\frac{x_2 - x_1}{L}\ln\eta\ );\ L \geq\ x_2\ \geq\ x_1\ \geq 0; \quad [5]$$

By using expressions [4] and [5], the discharge at the upstream end is found for any number {P} of water users along the canal:

$$q(0, t) = q(L, t)/\eta + \sum_{p\in\{P\}}[\ q_p(x, t)\times \mathbf{exp}\ (-\ \frac{x_p}{L}\ln\eta\ )]; \quad [6]$$

where $q_p(x,t)$ is the inflow to the "p"–irrigation contour in time "t", and $q(L,t)$ is the transit flow at the tail end of the canal.

Taking into account the "exp" and "ln" properties, equation [6] may be re-written as:

$$q(0, t) = q(L, t)\ /\eta + \sum_{p\in\{P\}}[\ q_p(t)\times\ \eta^{-(\frac{x_p}{L})}\ ]; \quad [6a]$$

It is interesting to note that the equations [6] and [6a] give correct values for the upstream discharge even under conditions of continuous lateral inflow (in this case, η>1).

The water distribution planning problem

An irrigation water distribution-planning problem arises at the stage of water demands accommodation, and is based on cropping patterns, available water volumes, and technical status of canals in the irrigation system. This problem is formulated in the following way: every irrigated area from the set {J} generates a water demand:

$$q^*_j(t) = \sum_{r\in\{R\}} F_{j,r} \times q^{\mathrm{N}}_{\mathrm{r,j}}\ (t)\ /\ \eta_j\ ,\ \forall\ j\ \in \{\mathrm{J}\},\ t \in \{\mathrm{T}\} \quad [7]$$

where $F_{j,r}$ is an area covered by crop "r" in an irrigation sector "j", $q^N_{r,j}(t)$ is the water supply rate for crop "r" in irrigation sector "j", and η_j is the irrigation efficiency in sector “j”.

This demand is met through the operation of offtakes:

$$q^*_j(t) \geq q_j(t) = \sum_{c\in\{C\}} \sum_{p\in\{P_c\}} q_{p,j}(t),\ \forall\, j \in \{J\},\ t \in \{T\} \qquad [8]$$

Besides, the specifications of the transit requirements are:

$$q^*_c(L,t),\ \forall\ c \in \{out\} \subset \{C\}\ ,\ t \in \{T\} \qquad [9]$$

and the water supply hydrograph is:

$$q^*_c(t) \geq q_c(0,t),\ \forall\ c \in \{inp\} \subset \{C\}\ ,\ t \in \{T\} \qquad [10]$$

where: {inp} and {out} represent the sources (inflows) and sinks (outflows) of the irrigation system, respectively.

Equations of conservation of water mass in the canals are satisfied when:

$$q_c^{\,max} \geq q_c(0,t) = q_c(L,t)/\eta_c + \sum_{p\in\{P_c\}} [\, q_p(x,t) \times \mathbf{exp}\,(- \frac{x}{L_c} \ln \eta_c)]; \qquad [11]$$

Besides, the conservation of water mass equations in system nodes are satisfied when:

$$\sum_{c\in C_k^+} q_c(L,t) - \sum_{c\in C_k^-} q_c(0,t) = 0;\ \forall\ k \in \{K\},\ t \in \{T\} \qquad [12]$$

where: C_k^+ is a set of canals entering the node “k”, C_k^- is a set of canals outgoing from the node “k”, ($C_k^+ \subset \{C\}$; $C_k^- \subset \{C\}$).

A time grid {T}={0, 1, . . . ,t } with a step-interval of 10-day periods is set for the planning problems. $q_c(0,t)$, $q_c(L,t)$ and $q_{p,j}(t)$, $\forall$ t∈{T}are unknown. Thus, the problem is divided into the following two:

- Problem (A) is the determination of water supply hydrographs at the upstream end of the irrigation system that meet the irrigated area demands and transit requirements, and also that satisfy the canals technical characteristics ; $q^*_c(t) \sim \infty$, $\forall\ c \in$ {inp}in this problem;
- Problem (B) is the distribution of the available water resources as supplied to the upstream end of the irrigation system, q*c(t), between irrigated areas and transit, while meeting the technical characteristics of canals.

The problem (A) has a trivial solution, but only for very simple irrigation systems (one head, tree-like structure of canal network) that may be considered only as an “exception to rule”. Generally, in order to obtain a unique solution, a criterion should be established that allows a qualitative rating of our actions. The simplified objective function that meets water mass conservation conditions, and generates the unique solution for the problem (A) can be written as:

$$f(q(t)) \Rightarrow \frac{\max}{q(t)} \left(\frac{\sum_{j \in \{J\}} q_j(t)}{\sum_{c \in \{inp\}} \lambda_c \times q_c(0,t)} \right), \ \forall \ t \in \{T\} \qquad [13]$$

where $q_j(t)$ is derived from equation [8], and $\lambda_c \geq 1$ are coefficients taking into account the inequality of water delivered from different sources, for instance: one source is a gravity intake in a river, while the second one is a pumping station. In the case of similar sources, all λ_c are equal to unity.

The occurrence of deficit in the system (strict observance of condition [8]) in solving the problem (A) means that a part of canals operate under load limit (those canals that meet equation [11]).

At the second stage (problem (B)), it is necessary to distribute available water in the best way. The "equity principle" consisting in equal cutting of all irrigation sectors dominates in this problem. The relative value of cutting is determined via the required and the available discharges as:

$$\beta(t) = \frac{\sum_{c \in \{inp\}} q_c^*(t)}{\sum_{c \in \{inp\}} q_c(0,t)}, \quad \beta(t) \leq 1 \ , \ \forall \ t \in \{T\} \qquad [14]$$

where $q_c(0,t)$ is the solution of problem (A), and $q^*_c(t)$ are the allocated water resources.

Let calculate the available water for irrigation sectors as follows:

$$q^{\sim}_j(t) = q^*_j(t) \times \beta_j(t) \ , \ \forall \ j \in \{J\}, \ t \in \{T\} \qquad [15]$$

and let introduce a new variable $\delta q_j(t)$:

$$\delta q_j(t) = [\, q^{\sim}_j(t) - q_j(t)]/F_j \ \geq 0 \ , \ \forall \ j \in \{J\}, \ t \in \{T\} \qquad [16]$$

where F_j is the area of the irrigation sector "j". By considering $\delta q_j(t)$ as a degree of deviation from the best water distribution, the expression below defines an objective function of the problem (B):

$$f(q(t)) \Rightarrow \frac{\min}{q(t)} \left[\sum_{j \in \{J\}} \delta q_j(t) \right], \ \forall \ t \in \{T\} \qquad [17]$$

The optimal control problem

The application of control theory methods to water distribution problems starts with the formulation of three key concepts, - determination of objective, formalization of the system trajectory and feasible control space. In the problems described in the previous section, the objective referred to water distribution that is to be achieved by searching, for each time lag, the best solution based on demand, available water volumes and the canal technical status in a specific time lag. Thus, components such as “objective” and “feasible control space” were present in the previous problems (the last component was available in an indirect form through various limitations). For control problems, the demand itself and the available water volume become functions of both external conditions and of solutions made in previous time lags. This influence is reflected through the “system trajectory” component. In our case, this component is an irrigation sector. For the planning problems, with the control period equalling a season and the averaging interval of ten days, such complication was of no use due to high uncertainty of weather conditions and of hydrological flow. The opposite is the case where the control periods equal one month or ten-day period and the averaging intervals are a day and less. In this case, water supplies to irrigation sectors depend on conditions of water application to particular crops. The irrigation sector, from the irrigation system perspective, is an end user. The main operational characteristics of the irrigation sector are:

a) Crop irrigation schedule;

b) Idle outflow to collector-drainage network.

These characteristics are determined inside a sector and depend on a number of parameters, such as crop type, irrigated field slopes, soil type, current climatic conditions, etc. The key characteristic for the irrigation system is (a) above, which violation leads to a two-parameter response. Shortening or augmenting the irrigation time duration causes an increased idle outflow (shortening may lead to increase in idle runoff, while augmenting may cause higher percolation losses). Shifts in the scheduling timing relative to the water application’s initial time leads either to over-moistening of the soil (early water application) or to crop productivity losses (delayed irrigation application). Since each canal in an irrigation system serves several irrigation sectors, for a 10-day based control, the problem is formulated as re-distribution of water resources between irrigation sectors in the best way. This problem, in contrast to the previous problems, has lower hierarchical level but directly concerns the irrigation system since actual crop irrigation water supply and flow fluctuations in canal sections depend on the system.

In order to solve the problem, which is usually referred to as “the problem of completing an irrigation schedule”, let consider the functioning of an irrigation sector under a set of crops. Water demand of each crop is estimated using the ISAREG model, which is expressed by a series of irrigation events, indicating the date of the water application beginning and the required water volume for each event. When an inflow volume (optimal for the given type of fields, soils, irrigation technique; etc.) is established for each crop, any deviation from it leads to an increase in operational losses. An example of changes in losses due to deviation from the fixed inflow volume is shown Fig. 2[2], which shows different losses due to increase or reduction of inflow (two different branches). Thus, under discharge increasing by 0.4 l/s (q = 2.5 l/s) losses are almost doubled; when decreasing by the same value, losses increase only by 10%. Taking into account that the irrigation technique is established for each crop and each field, namely an optimal discharge for given type of fields, soils, etc., deviations from lead to increased losses. Under this discharge, minimal losses in the field are provided (15% in present case), which sharply increase under less or higher discharges (Fig. 2). As it is evident from Fig. 2, losses are non-equivalent under discharge increase and decrease (two different branches). Such curves require that cubic (or higher) polynomials be applied; however, in case of minor deviations, a quadratic approximation can be used.

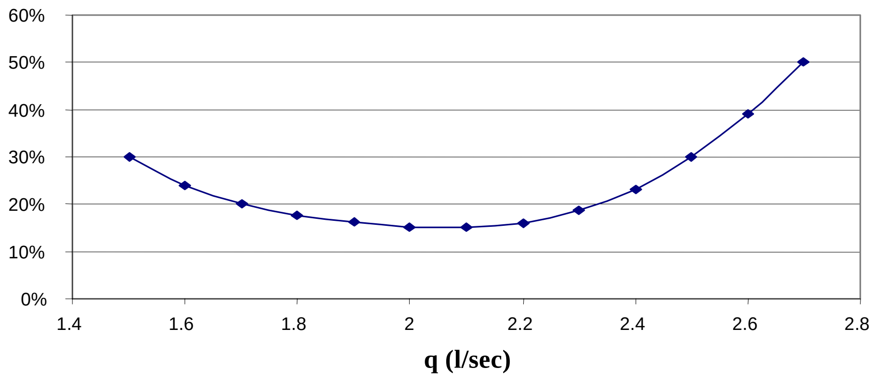

Fig. 2. Losses by inflow to furrow.

The dynamics of an irrigation event in this approximation can be described as:

$$F_{r,j} w^n_{r,j} = \int\limits_{t \in T^r_n} q_{r,j}(t) \times [\eta_{r,j} - \alpha_{r,j}(q_{r,j}(t) - q^0{}_{r,j}(t))^2] dt \qquad [18]$$

where: "j" is the index of the irrigation sector, "r" is the crop index, "n" is the number of the irrigation, $F_{r,j}$ is the area cropped, $w^n{}_{r,j}$ is the required crop water irrigation volume "n", $\eta_{r,j}$ is the efficiency of the applied irrigation technique, $\alpha_{r,j}$ is the coefficient of losses when deviating from fixed inflow, $q^0{}_{r,j}$ is the fixed inflow for a certain time lag, $q_{r,j}$ is the actual inflow in a given time lag, $T^r{}_n$ is the time of irrigation "n".

The equation [18] estimates crop demand, where the unknown values are: $T^r{}_n$, n={0,1,…,N^r} – irrigation event number for crop "r" and $q_{r,j}(t) \geq 0$. Based on [18], equation [8] is re-written as:

[2] Data source: SANIIRI's (Central Asian Irrigation Research Institute) data.

$$\sum_{r\in\{R^j\}} q_{r,j}(t) = \sum_{c\in\{C\}} \sum_{p\in\{P_c\}} q_{p,j}(t),\ \forall j \in \{\mathrm{J}\},\ t \in \{\mathrm{T}\} \qquad [19]$$

where $\{R^j\}$ is a set of crops in sector "j".

The irrigation system's water supply and distribution dynamics are described by equations [9] –through [12]. By assuming that each irrigation event date is known, the following criterion can be enunciated for irrigation water optional distribution:

$$\aleph(q_{r,j}(\bullet)) = \sum_{j\in\{J\}} [\sum_{r\in\{R^j\}} [\int_{t\in\{T\}} q_{r,j}(t) \times \alpha_{r,j}(q_{r,j}(t) - q^0{}_{r,j}(t))^2 dt]] \rightarrow \boldsymbol{min} \qquad [20]$$

The criterion [20] reflects water savings in irrigation sectors but does not take into account the characteristics of on-farm irrigation network performance. Channels abrupt flow fluctuations cause unavoidable losses in form of idle discharges, and its volume can be formalized as:

$$\mathrm{W}(q_c(\bullet)) = \sum_{c\in\{C\}} \int_{t\in\{T\}} \beta_c \times q_c(t) \times [\frac{\partial q_c(t)}{\partial t}]^2 dt,\ \forall j \in \{\mathrm{J}\},\ t \in \{\mathrm{T}\} \qquad [21]$$

To complete the formulation of optimal control problem, functions should be identified among which the point of extremum (***min***) is to be found [20]. The problem [9]-[13], [18]-[20] refers to those of optimal control with fixed time and for which, a set of $q_{r,j}(\bullet)$, is a feasible solution when the following conditions are satisfied:

1. Vector-function $q_{r,j}(\bullet)$ is defined and piecewise continuous in segment *{T};*
2. Condition [18] is satisfied for all $t\in\{T\}$;
3. Boundary conditions [9],[10] are satisfied;
4. Functions $q_{out}(t)$ and $w_{r,j}(t)$ are defined and piecewise continuous in segment *{T},* (these functions are uncontrollable since they characterize transit requirements and irrigated area demand).

The point of extremum will be found among the above-mentioned feasible solutions [20].

This problem is called on-line control of water distribution in irrigation systems. Based on the solutions of this problem, water supply volumes are defined more exactly, and depending on allocated water limits, the hydrostructures operation regime is assigned. The next stage in solving the on-line control problem is the correction of planned inflow according to the actual water-management situation. In terms of optimal control theory, the second task is classified as a problem of control synthesis or designing of backlink operator (Moiseyev, 1971). This problem fundamentally differs from the previous one, determination of the program trajectory based on both quality criteria involved in functional formation, and solution procedures. The purpose of this problem is to determine the found program trajectory, which is final in any control process. The importance of correct solution for this problem is that, while mistakes or deviations in the program's trajectory lead to economic losses, the incorrectly designed backlink operator sharply reduces controllability of the whole irrigation system and causes an increased operational water loss. Generally, this problem is more complex than the direct optimal control one due to an absence of the regular solution procedures for the former and lack of necessary conditions that stand as the starting point for the development of analytical models.

Results

Farm "Azizbek" in Akhunbabayev district, in Fergana province was selected as a field study site. Water was delivered from the head of "Pakhtakor 4" in three main directions via nine canals (C1 to C9). Canal C2 delivers water for irrigation of given site also includes water as transit. The irrigation system layout is shown in Fig. 3, where each outlet corresponds to each field.

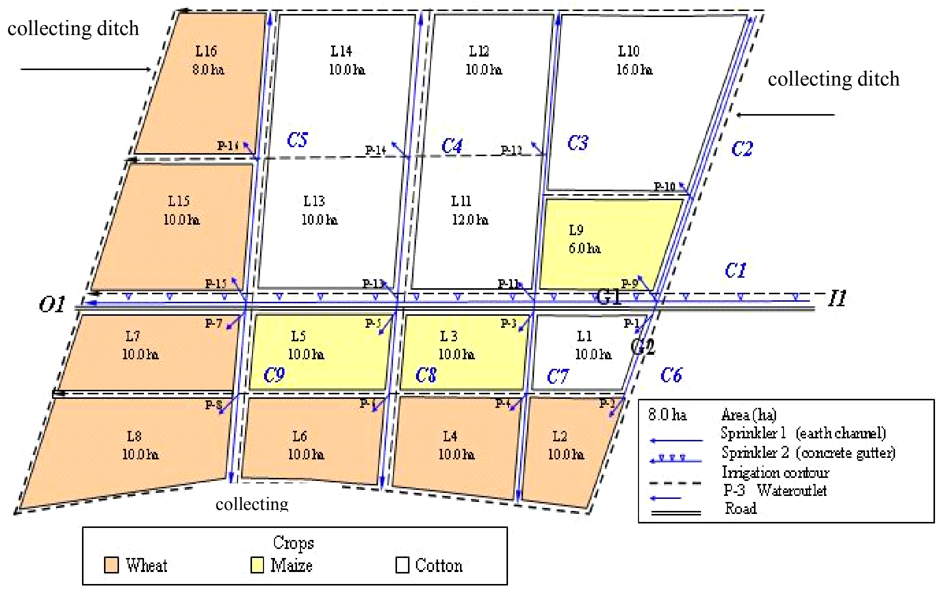

Fig. 3. Irrigation system layout of in the site under study.
(symbols: I1 – inflow (to irrigation sector); O1 – outflow (transit); G1, G2 – gauging sites; C1-C9 – channels; L1-L16 – irrigated fields; P1-P16 – outlets to the fields)

Irrigation schedules by fields in farm "Azizbek" (under minimum yield losses, optimal irrigation option) were defined with model ISAREG and are referred in Tables 1 and 2.

The ISAREG model (Pereira *et al.*, 2003; Fortes *et al.*, 2005) produces an irrigation schedule, which may be optimized relative to irrigation depths and dates to couple with the limitations of the irrigation network and flow capacity; the operation regime (uniformity of irrigation intervals, stability of flow); and the sector optimal demand solution through the SEDAM DSS model (Gonçalves *et al.*, 2005b).

Table 1. Field irrigation norms and terms according to irrigation scheduling requirements (irrigation depths for winter wheat (mm)).

Field nº	2	Date	23/10	19/04	9/05	29/05
		Depth	80	80	80	80
	3	Date	23/04	18/05	5/06	
		Depth	82	83	84	
	4	Date	19/10	20/04	10/05	27/05
		Depth	80	80	80	80
	5	Date	22/10	18/04	13/05	2/06
		Depth	80	80	80	80
	6	Date	17/10	1/05	25/05	
		Depth	80	84	85	
	7	Date	12/10	27/04	19/05	8/06
		Depth	80	80	80	80
	8	Date	13/10	26/04	19/05	7/06
		Depth	80	82	82	80
	9	Date	18/10	28/04	17/05	5/06
		Depth	80	80	80	80
	15	Date	17/10	29/04	21/05	12/06
		Depth	80	82	80	80
	16	Date	11/10	25/04	17/05	7/06
		Depth	80	80	80	80

term – recommended date of irrigation, norm –irrigation depth

Table 2. Field irrigation norms and terms according to irrigation scheduling requirements (Irrigation depth for cotton (mm)).

Field nº								
	1	Date	16/05	05/06	23/06	5/07	21/07	7/08
		Depth	80	80	80	80	84	95
	10	Date	14/05	3/06	21/06	3/07	19/07	5/08
		Depth	80	80	80	80	90	93
	11	Date	15/05	4/06	22/06	4/07	20/07	6/08
		Depth	80	80	80	80	83	95
	12	Date	14/05	3/06	21/06	3/07	19/07	5/08
		Depth	80	80	80	80	90	100
	13	Date	18/05	7/06	25/06	7/07	22/07	11/08
		Depth	80	80	80	80	85	92
	14	Date	18/05	7/06	25/06	7/07	23/07	9/08
		Depth	80	80	80	80	90	95

term – recommended date of irrigation, norm –irrigation depth

As a result, the produced schedule was found quite unsatisfactory for the system requirements (Fig. 4a) in terms of both maximum flows (up to 280 l/s, given the admissible one of 200 l/s) and flow fluctuations. Anticipating these limitations from using in separate the ISAREG model and the field irrigation estimations, the DSS models SADREG and SEDAM (Gonçalves *et al.*, 2005a, b) were developed but there was no time to produce its test in this practical application.

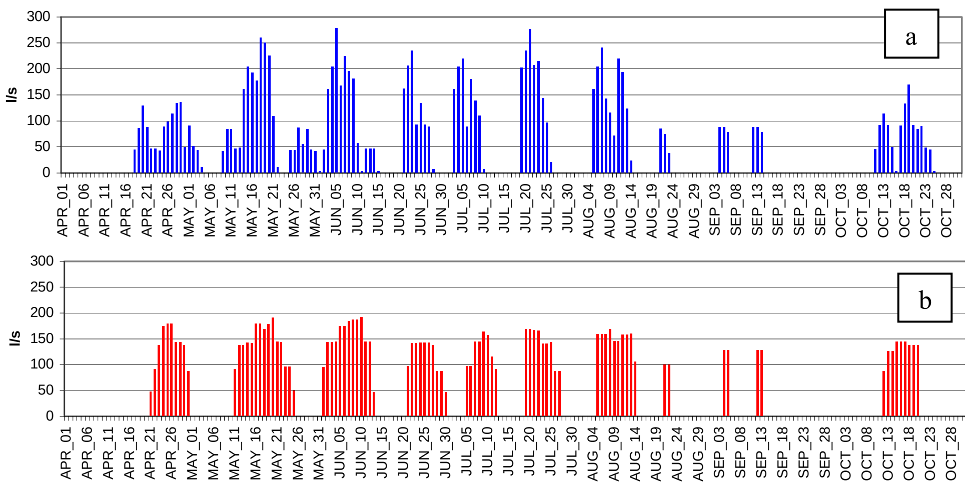

Fig. 4. Results of demand modelling using ISAREG (a) and by SIC ICWC limiting discharges to 200 l/s (b). The actual schedule is given in Fig. 1.

Modelling of an optimal option based on canal requirements was implemented under a number of assumptions, based on the irrigation technology and agricultural operations: deviations in irrigation dates not exceeding 4 days and in irrigation time ± 5%; irrigation interval of 10 to 15 days were obtained The optimal regime is also shown in Fig. 4b, which meets the above-mentioned requirements.

Two assessments were made by the preliminary preparation: actual water delivery and allocation in the year 2001, using ISAREG without following optimizing rule, and using the fore mentioned mathematical procedure (Table 3).

Table 3. Comparison of two alternatives for demand and delivery scheduling with the current delivery mode.

Indicators	Current management rules	Using ISAREG without optimization	Mathematical optimization modelling
Degree of water provision:			
by volume*	1.876	0.6	1.0
by time	± 12 days	± 0 days	± 3 days
Equity allocation**	1.8	1.6	1.0
Operational losses in canals (%)	26	24	3
Operational losses in fields (%)	22.7	15.0	15.0
Degree of flow stability**	1.8	2.1	1.0

*relation of actual water delivery to water required
**deviation from average indicator

Option 1 (present rules) resulted in a huge quantity of extra water delivery, large operational losses in fields and canals, very unstable canal working conditions and low level of equity in allocation (Fig. 5). Such inequity reflected not only on the indicators of one irrigation, but even on the degree of water satisfaction for the whole vegetation period (Fig. 6). Thus, the comparison (Table 3) gives the following:

- Actually water consumers received by 87% more water then it was required with irrigation terms shift by ±12 days; water distribution evenness was 1.8, total operational losses in the field and canals reached almost 50%; and the stability degree was 1.8;
- Under irrigation according to ISAREG requirements, there were shifts in irrigation terms, but satisfaction of all needs was impossible because the canal capacity would be exceeded; resulting operational losses were 39%, unevenness and instability amounted to 1.6 and 2.1, respectively;
- In case of suggested approach, the deviations from the established irrigation terms didn’t exceed ±3 days; Total operational losses were 18%, while stability, availability and evenness were equal 1.0.

The second option does not allow to be satisfied by the canal characteristics and results were not satisfactory. However this could be expected because the ISAREG model is designed for field irrigation only and its use at sector or higher level requires other approximations, as shown for applications in North China (Gonçalves *et al.*, 2003).

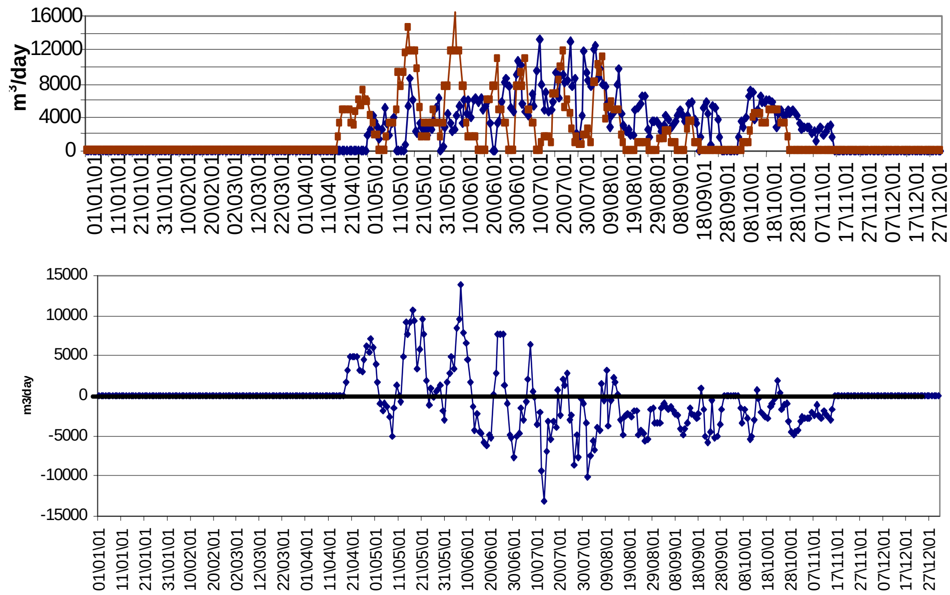

Fig. 5. Above: comparing actual deliveries with the field demand (m^3/day) along a cotton crop season in a canal in Fergana, and, below, the difference between delivery and demand (m^3/day).

Contrasting, the model of water delivery and water allocation to fields based on the equation of combined functioning of delivery and demand of each fields produced:

- minimum runoff out of fields as operational waste;
- minimum operational losses in canals;
- maximum approaching the time table's and crop water demands satisfaction according to demand formulated using ISAREG.

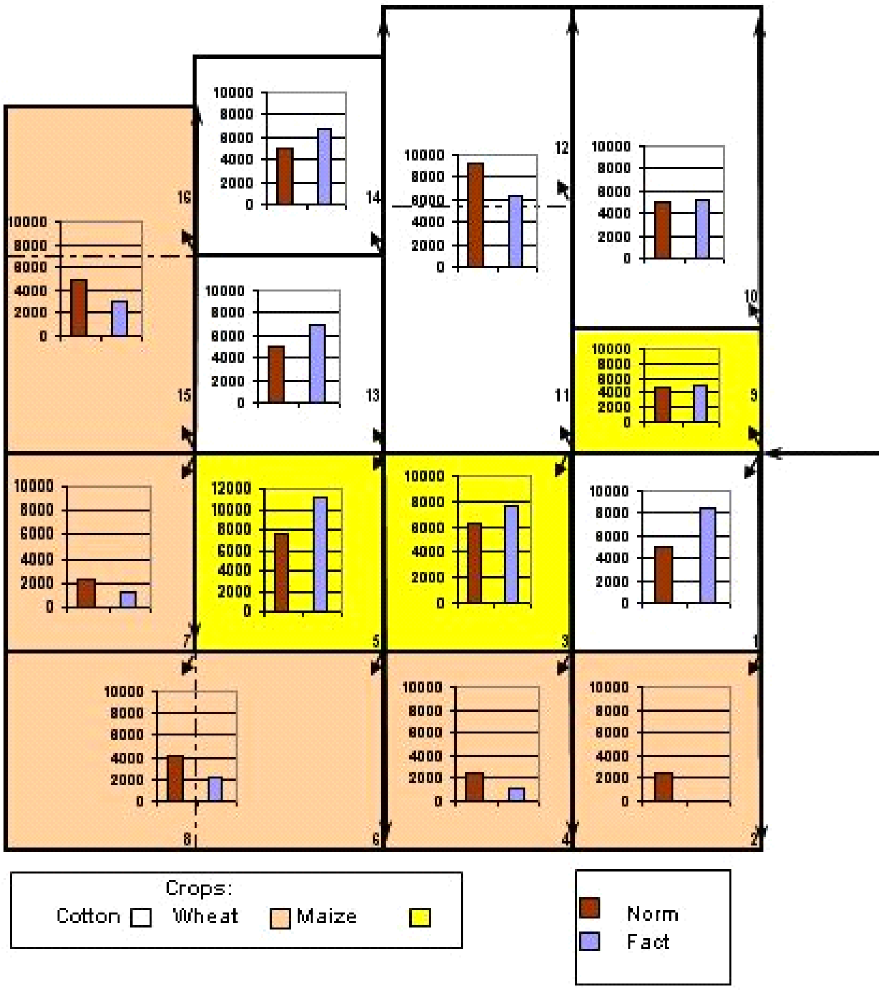

Fig. 6. Planned (norm) and actual (fact) water volumes (m^3/ha) delivered for field irrigation during the cotton growing season (April – September 2001) at the Azizbek farm (fields are the same as in Fig. 3.).

The recommended modelling method described herein may increase the total efficiency of the farm water use by more than 30%. Further combining this method with the DSS SEDAM may lead to further improvements.

Project findings led to another main output since it is shown that the implementation of IWRM can not orient only to institutional and legal reforms but must include as a main component the adoption of new managerial and technical tools for water management and irrigation farming. This component of IWRM should give clear understanding where, how and which tools can be used to face mismanagement in this sector, which is main disadvantage of present situation in Central Asia.

Expected results from a new joint engineering and IWRM managerial aspects can refer to the transfer to new crop and field oriented water consumption and use into the consideration of changes related to climatic deviation relative to average evapotranspiration demand and to local soil conditions with a potential saving of 12 to 15% of water volumes. In addition, minimizing operational water losses caused by separateness and absence of interconnection between hierarchical levels may lead to 8 to 15% savings in water delivery as well as to an increase of land productivity by 20 to 30%. However, further developments are required to effectively install in the canal management practice the modelling approaches herein presented.

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