FEATURES OF OPTIMIZING IRRIGATION MODES ALGORITHMS UNDER CLIMATE CHANGE.

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Annotation

This article examines the irrigation optimization specifics in cases of extreme water shortages, when water costs represent a significant fraction to crop yield value. Using the optimization method as an example, in case of "inexpensive irrigation" water, it demonstrates what need to pay special attention when selecting the optimal regulation range.

Key words: irrigation regime optimization; optimal range; plant requirements and melioration regime.

Introduction. One of the key aspects of the formal irrigation model is the optimization criteria used to determine irrigation schedulers and rates. These criteria are set under uncertain weather conditions, which can affect to plant growth and development. During climate change, this circumstance is especially critical**.**

The information on the basis of which management is carried out is the current data on productive soil moisture reserves. [Shabanov et al., 1990]

Mathematically, the most acceptable method for such control is

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stochastic adaptation theory. In this formulation, irrigation management is considered as an optimal procedure for a sequential process with a given number of steps and a certain loss function at each step.

The management objective is to maintain moisture at an optimal level, from the standpoint of plant and soil biota requirements; any deviation from the optimal moisture level reduces productivity at every step.

Irrigation (management) within the optimal range to the right of the maximum productivity point results to unnecessary irrigation water consumption. This leads to crop losses due to nutrient leaching, rising groundwater levels, etc.

Thus, optimal management must satisfy a certain compromise relationship that considers productivity losses, management costs, including the cost of water, and compensation for environmental damage that occurs when the reclamation regime is not followed, and soil biota.

Typically, the future weather conditions is unknown, so the choice of control actions at each step is carried out so that with known actual humidity W_i the mathematical expectation of the total damage during control, calculated relative to the conditional distribution of the random variable of field humidity at the next step, was minimized W_{i+1} at known humidity W_i.

To solve this problem, it is necessary to define models for predicting field moisture and calculating productivity losses due to deviations in moisture content from its optimal value.

The most acceptable model describing the dynamics of field moisture during the growing season is the model obtained by combining the conventional balance model of moisture transfer [Maksimov et al., 2022] and the model obtained on the basis of representing the dynamics of moisture change by a first-order Markov process [Shabanov, 1981].

The mathematical representation of this model is reduced to the equation:

$$W_{i+1} = \alpha_i \cdot W_i + \beta_i + m_{\mathrm{i}} + Z_i,$$

where W_i — humidity at the i-th control step; α_i, β_i - some constants defined for a given step; m_i - management action (analogous to irrigation norm); Z_i - random disturbance of the system.

Moreover W_{i+1} is considered as a random variable with a mean value $\overline{\mathrm{W}}_{in}$.

To determine the damage (loss of productivity) when the current humidity deviates from a certain optimal value, from the respective of plant requirements, a simple productivity model could be used [Golovanov, 2008; Shabanov, 1973]:

$$S_i = \left(\frac{W_i}{W_{opti}}\right)^{\gamma i W_{opti}} \cdot \left(\frac{1-W_i}{1-W_{opti}}\right)^{\gamma i(1-W_{opti}))},$$

where S_t - relative productivity at the i-th moment of vegetation; γ_i - is a parameter characterizing the adaptive capabilities of the plant, generally depending on a combination of environmental factors; W_i; W_{opt} - current and optimal moisture reserves in the soil.

During the growing season, the productivity of the i-th crop can be calculated using the dependence:

$$\overline{S_J} = \sum_{t=1}^{j} n_{ij} S_{ij},$$

$\overline{S_J}$ - relative yield of the j-th crop in a given year;

n_{ij} - “weight” of each phase of vegetation is a coefficient showing the influence of moisture in a given phase of vegetation [Shabanov, 1981].

This model assumes that, under optimal life-support conditions, each agricultural crop can be assigned a certain trajectory of productivity accumulation, which is determined by biological time, which expressed as the sum of effective temperatures.

This means that under optimal conditions, the total accumulated productivity of agricultural crops is described as a function of biological time and reaches 100% of the potential of the variety in the given natural and climatic conditions by the end of the growing season.

Therefore, for any fixed increment in effective temperatures there is a fixed increment in productivity, and the final relative productivity of the optimal conditions could be expressed as:

$$\sum_{\tau=t^{\circ}}^{\tau=t_K} p_{\tau} = 1,$$

where t° - vegetation resumption temperature, t_K — end of growing season temperature, τ - discrete interval of increment of effective temperatures over a certain period of time, p_{τ} - increase in productivity.

The biological meaning of this function corresponds to the growth function, determined from the position of the mature plant (for example, accumulation of biomass).

In this model, final productivity corresponds to potential relative productivity, the value of which depends on factors such as the availability of photosynthetically active radiation (PAR) to crops, the availability of nutrients, the maximum productivity of a given variety, etc.

It is not hard to see that the S (W) dependence has a dome-shaped character. In the optimal moisture range area, on irrigated lands S>0.6, this dependence is well described by a quadratic deviation function of the current moisture from the optimal value, that is:

$$S_i = g_i(W_{opt} - W_i)^2 + b_i$$

where g_i, b_i - coefficients depending on the biological control object, W_{opti} - optimal humidity value, g_i - function of the temperature factor.

Thus, when the field humidity deviates from the optimal humidity W_{opt} loss of productivity at any step in the range 0,6 <S <1 can be assessed by dependence:

$$\Delta S_i = g_i(W_{i+1} - W_{opt})^2,$$

Then, the management of the formation of plant productivity in irrigated fields can be considered as the optimization of a sequential process with a given number of steps and a quadratic loss function at each step.

In case of significant deviations in humidity from W_{opt} the type of objective function needs to be changed.

According to the theory of optimal stochastic control, the minimum mathematical expectation of the total damage to productivity from management (irrigation) relative to the conditional distribution of future values of field moisture with known current moisture is achieved with management m_i (according to Zemlyanov Yu.M.) [Shabanov, 1990]:

$$m_i = \frac{q_i W_{opt} + A_i B_i - (q_i + A_i)(\alpha_i W_i + \beta_i)}{q_i + A_i + R_i},$$

where Ai и Bi — constants defined below; Ri - control cost at the i-th step.

The values A_i, B_i are determined by recurrent formulas, starting from the last step of the controlled process.

With a daily control step, the total number of steps until the end of the crop's vegetation period is found from the equation:

$$N_i = (t_K - t_{\text{cp}i})/\Delta t_i$$

where t_{cp} — actually accumulated effective sum of temperatures by the i-th step; Δt_i - temperature coefficient reflecting the average daily increase on effective temperature; Ni — number of steps remaining until the end of the growing season.

At each step, using the equations for calculating Ai and Bi, their values are calculated for each of the remaining steps. Then, using the actual moisture content, the current management value m_i is calculated at that step. Positive values of mi accumulate until their sum reaches to the irrigation rate value. The step number at which the total management value corresponds to the irrigation rate is used as the start day number for irrigation.

Time for irrigation is calculated using the formula:

$$\tau = \frac{F \cdot m}{8.64 \cdot Q \cdot K_{day}};$$

where F - field area, Q — machine consumption, K_{day}- daily occupancy rate.

In the equations determining the control value m_i, the management cost Ri (which may include the cost of water) plays a key role. Its variation serves as a regulator that allows for the integration of management in individual fields into united irrigation control system.

In the formal model, the main link in the unification of management in individual fields was the limitation on the capacity of the irrigation network and the limitation on the water resource.

Using various management "costs", irrigation rates and crop productivity are calculated for individual irrigated fields. This is the basis for constructing irrigation production functions that link irrigation rates, water supply, expected crop productivity, and management costs.

The assumption of the “quadraticity” of the amelioration regime function, on the one hand, gives a fairly good estimate of the optimality of the period on water factor, and on the other hand, allows us to solve the problem of optimal stochastic control using fairly simple methods.

All of this provisions works good with cheap or free irrigation water.

If the cost of water or the damage from its negative impact on soil biota is comparable to the cost of production, the form of the amelioration regime function begins to play a significant role. In this case, a slight deviation from a fairly narrow and asymmetrical “optimal” range at $S \geq 0.8$ can make land reclamation economically (or environmentally) unprofitable.

This is most clearly manifested in ecosystem reclamation, for example, in catchment area reclamation. [Nikolsky, Aidarov, 2023].

By selecting the maximum productivity of the irrigated area as the objective function and using the dynamic programming method for the water resource available at a given time, its optimal distribution between irrigation fields is found depending on the current moisture content of each field and the asymmetry of the response at different points of the reclamation regime curve.

Based on the optimal and expended water resources required to irrigate each field for the remainder of the growing season, the corresponding management cost can be determined. The management cost estimate for each field, as well as the necessary coefficients for calculating the management value, are recalculated during the growing season, based on the actual accumulated temperature and observed field moisture.

A similar management re-assessment procedure can be used to limit irrigation in the event of a forecast of soil structures deterioration or a threat of flooding of irrigated lands and adjacent territories.

Conclusion. Analysis of the equations for finding optimal control led to a following conclusion. If the control cost is zero, the required control action is estimated as the difference between the optimum moisture content and the current field moisture content, i.e., it is reduced to the standard procedure used in all irrigation management recommendations for operating irrigation systems.

The needs for more complex structures arises only when management is carried out with a limited water resource or when it is necessary to take into account all aspects related to irrigation under climate change (loss of soil fertility, sudden droughts, flooding and waterlogging, etc.).

It is obvious that further development of the irrigation systems operation theory should be carried out on the basis of soil conservation and resource-saving technologies, which will lead to the need for more complex mathematical software (Shabanov, Bondarik; 2027; in press), the use of neural networks and modern tools for monitoring plant habitat factors and soil biota.

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