Forecasting methods for the total evapotranspiration of fodder crops in arid conditions of Kalmykia

M M Okonov, T I Bakinova, E A Jirgalova and S V Ubushaeva

Kalmyk State University named after B.B. Gorodovikov, 11, Pushkin st., Elista, 358000, Russia

E-mail: okonov.51@mail.ru

Abstract. In 1995-2015, in the dry steppe and semi-desert zones of the Caspian lowland, a series of experimental studies were conducted on brown and light chestnut soils to establish the total evapotranspiration of annual fodder crops using irrigated arable land. Four different methods were studied; the water balance method was used as a control one. The temperature coefficients of the total water consumption, as well as the coefficients of an air humidity deficit combined with the scale of biological time of vegetation were determined. Specified coefficients of water consumption were determined; they were differentiated depending on different conditions of mineral nutrition and the planned yield. For production conditions, biological and mathematical models of dependence have been developed in order to determine an optimal water regime in the arid zone. Based on the obtained experimental data, the convergence of the calculated values obtained by the bioclimatic and water balance methods was achieved. The planned crop yield was produced.

1. Introduction

In the world practice of irrigation, among the methods for calculating the total water consumption, one can mention the method of evapotranspiration of crops based on the water balance equation, the sum of average daily temperatures and deficit of air humidity, evaporation. For example, in Germany and Hungary, the Klatt’s method is often used to determine the demand for irrigation, according to which the calculation of evapotranspiration of crops is based on data on temperature and relative humidity. According to meteorological observations, they build diagrams and calculate the moisture deficit. With an increase in moisture deficit to 20-40 mm, irrigation should be 20 mm. At the same time, data on the available moisture are also taken into account. In Italy, France, and the USA, indicators of evaporation are widely used to determine the need for irrigation moisture. This method is based on the fact that evapotranspiration of crops with an optimal moisture supply corresponds to evaporation from the water surface and depends on temperatures and humidity, solar radiation, and the wind speed. In addition to these methods, calculation formulas for determining the need for agrophytocenoses in soil moisture (S.V. Thorngveit, H.V. Blaini, V.D. Criddle, H.L. Penman) were widely used in the United States and England. In the Russian Federation, for the method by A.N. Kostyakov was widely used for this purpose. [14] The water consumption of crops (E) was determined by a simple dependence \( E = K_x \times Y_{pl} \), where \( K_x \) is the coefficient of water consumption, \( \text{m}^3/\text{t} \) obtained by the experimental method, \( Y_{pl} \) is the planned yield, \( \text{t}/\text{ha} \). The disadvantage of this method is that the coefficients of water
consumption of different crops vary in the irrigation zones depending on agro-climatic conditions and the yield. An analysis of the development of irrigation in modern Russia, the CIS countries and abroad identified changes in approaches to determining the evapotranspiration value, and irrigation regimes. In this regard, researchers use calculation methods by A.M. and S.M. Alpatyev, K.G. Lgov, D.V. Shtyko [4,12] et al. based on the use of temperature coefficients of evaporation, as well as relative humidity of crops during the growing season or calculation period in the form of the following dependence: \( E = f \left( f_m \right) \), where \( f_m \) is one or more meteorological factors. Despite all the objective difficulties and inaccuracies, the bioclimatic method has significantly improved the general method for establishing the total evapotranspiration and provides a more realistic opportunity for the operational management of the soil water regime in crops. [7,10]

The aim of the research is to develop bioclimatic methods for predicting irrigation regimes and total evapotranspiration values in arid conditions of light chestnut and brown semi-desert soils during the cultivation of annual fodder crops for single-species and mixed sowings. [3,6,8]

2. Methods and conditions
The Republic of Kalmykia is located in the arid zone of the southeast of the European part of Russia. The climate is arid, the aridity index varies from 0.20 to 0.47, while the average annual precipitation varies from 180-200 to 350-360 mm. The sum of daily average temperatures is 3450-3550 °С [1]. Brown semi-desert soils have an alkaline reaction, a low humus content of 1.1-1.3%. The content of mobile phosphorus (P2O5) is 16-18 mg/kg, exchange potassium (K2O) is 340-400 mg/kg of soil. According to the natural agrochemical background, light chestnut soils are better than brown soils, the humus content is 1.3-1.5%, the mobile phosphorus content is 2.0-2.2 mg / kg and the potassium content is 300-350 mg / kg. The highest field humidity (HB) in the meter horizon is 20–21%, the wilting moisture is 9–10%, the total soil porosity is 47–48%, and the soil compaction density is 1.41–1.43 t/m³. [2]

Experimental studies were carried out in 1995 - 2015 to analyze water regimes of light chestnut and brown semi-desert soils with an optimal threshold for pre-irrigation moistening of 75-80% of NM in irrigated crops, and predict the total evapotranspiration of annual feed crops by bioclimatic methods in comparison with the method of water balance. When conducting experiments, the methods by B.A. Dospekhov [9], B.D. Kiryushin [11], VNIIGiM (2001) and VNIOZ (2008) guidelines, “the Adaptive-landscape farming system of the Republic of Kalmykia” [13] were used. Statistical processing of the results was carried out in Statistica 10.0 and Microsoft Excel XP.

3. Results and discussion
When developing and implementing the crop cultivation technology, it is necessary to determine moisture resources to obtain the planned yield, as well as availability of operational information on the moisture demand dynamics during the growing season in specific weather conditions on irrigated fields. The method of water balance cannot ensure the required efficiency of the water regime. Therefore, in 1995-2015, in the subzones of the dry steppe and semi-desert of the Caspian lowland, we conducted studies to determine the total evapotranspiration of annual fodder crops by bioclimatic methods in comparison with the method of water balance. When conducting experiments, the methods by B.A. Dospekhov [9], B.D. Kiryushin [11], VNIIGiM (2001) and VNIOZ (2008) guidelines, “the Adaptive-landscape farming system of the Republic of Kalmykia” [13] were used. Statistical processing of the results was carried out in Statistica 10.0 and Microsoft Excel XP.
temperatures biologically required for the crop production and short-term and medium-term weather forecasts for the nearest pentad and decade, it is possible to predict the onset of the next phenological phases with an acceptable accuracy. Discrepancies between calculation and phenological dates did not exceed ± 2-3 days.

### Table 1. Bioclimatic coefficients for predicting water consumption (Kt; Kd) by interphase periods and during the growing season when growing two crops per year

| Interphase period                          | Total water consumption, mm | Duration, days | Biological need for heat, °C | The sum of air humidity deficit, gPa | Forecasting formula for total water consumption E, mm |
|-------------------------------------------|-----------------------------|----------------|------------------------------|-------------------------------------|--------------------------------------------------|
| Bean-bluegrass mixture - the first crop   |                             |                |                              |                                     |                                                  |
| Sowing-seedlings                          | 22,3/24,2                   | 11±1           | 130/131                      | 77/76                               | 0,171/0,185 t1, 0,290/0,318 d1                  |
| Seedlings-tillering                       | 129,6/117,4                 | 30±2           | 545/564                      | 363/368                             | 0,238/0,208 t2, 0,357/0,319 d2                  |
| Tillering-shooting                        | 172,1/198,0                 | 23±2           | 499/544                      | 348/364                             | 0,345/0,364 t3, 0,494/0,544 d3                  |
| Shooting-heading of panicles              | 38,1/43,0                   | 6±1            | 117/121                      | 90/91                               | 0,326/0,56 t4, 0,423/0,474 d4                  |
| Sowing-mowing                             | 362,1/382,6                 | 70             | 1219/1360                    | 878/899                             | 0,280/0,281 t1, 0,412/0,426 d1                  |
| Corn and soybeans - the second crop       |                             |                |                              |                                     |                                                  |
| Sowing-seedlings                          | 30,2                        | 12±2           | 202                          | 121                                 | 0,149 t1, 0,249 d1                              |
| Seedlings-4-5th leaf                      | 51,0                        | 14±2           | 285                          | 189                                 | 0,179 t2, 0,269 d2                              |
| Booting                                   | 333,0                       | 45±2           | 1073                         | 672                                 | 0,310 t3, 0,495 d3                              |
| Heading of panicles                       | 35,3                        | 7±1            | 98                           | 78                                  | 0,360 t4, 0,452 d4                              |
| Sowing mowing                             | 449,5                       | 78             | 1658                         | 1060                                | 0,271 t1, 0,424 d1                               |
| Corn and sunflower - the second crop      |                             |                |                              |                                     |                                                  |
| Sowing-seedlings                          | 25,8                        | 10±1           | 195                          | 163                                 | 0,132 t1, 0,158 d1                              |
| Seedlings-4-5th leaf                      | 47,3                        | 12±1           | 280                          | 192                                 | 0,169 t2, 0,246 d2                              |
| Booting                                   | 283,8                       | 45±2           | 922                          | 550                                 | 0,308 t3, 0,516 d3                              |
| Heading of panicles                       | 33,8                        | 6±1            | 99                           | 79                                  | 0,341 t4, 0,429 d4                              |
| Sowing mowing                             | 390,7                       | 73             | 1496                         | 984                                 | 0,261 t1, 0,397 d1                               |

Having data on the reserves of productive moisture in the active calculated soil layer, it is possible to predict the cumulative water consumption of crops, and the next irrigation periods, using the
temperature coefficients (Kt) and the air humidity deficit coefficient (Kd). The dynamics of the average values of temperature coefficients of evaporation (Kt) and bioclimatic coefficients (Kd) for the interphase periods and for the vegetation of annual plants in mixed sowings when growing two crops per year is presented in Table 1.

In the sowings of the early spring legume-bluegrass mixture, the bioclimatic coefficients (Kt and Kd) were minimal at the beginning of the growing season; during the periods of the most active growth, their values sharply increased. The maximum temperature coefficient (Kt) for maintaining optimal soil moisture (75–80% HB) was 0.326–0.356 and the bioclimatic coefficient Kd was 0.494–0.544. In general, the total moisture consumption, that is, the total water consumption can be predicted using the equations: \[ E = 0.281 \sum t \] and \[ E = 0.426 \sum d, \text{ mm} - \text{for the central and eastern zones of the Republic of Kalmykia.} \]

The same dynamics of the bioclimatic coefficients of total evaporation, depending on the agrometeorological conditions for the interphase periods was observed for corn-soybean and corn-sunflower mixtures. To achieve the mowing ripeness of the corn-soybean mixture, 1658 °C of active temperatures are required. With a total of 1060 gPa of air humidity deficits, 449.5 mm of moisture are spent on corn-soybean crops. The value of these indicators for the corn-sunflower mixture is smaller. The total demand for heat resources amounted to 1469 °C, and the total moisture consumption was 390.7 mm. The average values of bioclimatic coefficients were used for calculating corn-soybean evapotranspiration by the equations: \[ E = 0.271 \sum t_{1-4} \] and \[ E = 0.424 \sum d_{1-4}, \text{ mm}, \text{ and corn-sunflower evapotranspiration by the equations} \[ E = 0.261 \sum t_{1-4} \] and \[ E = 0.397 \sum d_{1-4}. \]

When growing three crops a year, the intermediate sowing of winter rye during the first crop used 1157 °C of active temperatures. Since the date of sowing and until winter, for normal wintering, the sum of active temperatures required was 600 °C. The need for heat resources from the resumption of spring vegetation to mowing ripeness (the beginning of winter rye earning) is 530 °C.

An analysis of the results has identified that the water consumption of winter rye during the autumn growing season can be determined by the equations: for the dry steppe zone of Kalmykia - \[ E=0.118 \sum t \text{ and } E = 0.253 \sum d; \] for the semi-desert zone - \[ E = 0.139 \sum t \text{ and } E = 0.264 \sum d. \] In general, during the growing season, the temperature coefficient of evaporation (Kt) varies within the range - 0.225 - 0.239 \( \sum t \), and the bioclimatic coefficient for air humidity deficit (Kd) varies from 0.438 to 0.469 \( \sum t \). To achieve ripeness of the corn-sudan mixture, the sum of 1389-1462°C is required; to achieve ripeness of the corn-sorghum mixture, the sum of 1434°C is required. The coefficients of the biological curve of moisture consumption increase as the growth of the aboveground biomass of plants increases. The maximum values of Kt and Kd fall on the phases of shooting and heading of Sudan grass, corn and sugar sorghum (Table 2). The average values of bioclimatic coefficients are the same, which is due to fairly close and stable agrometeorological conditions.

Based on the data in Table 2, it is possible to predict the total water consumption of annual fodder crops (E, mm) in the dry steppe and semi-desert areas of the Caspian lowland using the following formulas: for corn-Sudan grass mixture:

\[ E = 0.269 - 0.272 \sum t \text{ and } E = 0.397 - 0.402 \sum d; \]

for the corn-sorghum mixture

\[ E = 0.276 \sum t \text{ and } E = 0.365 \sum d. \]

The growing Sudan aftergrass forming the third crop completes the vegetation with a set of sums of average daily temperatures up to 1051 - 1146 °C. In this case, the tillering phase accounts for 413 - 456 °C, the shooting phase accounts for 535 - 607 °C. The total water consumption from the beginning of regrowth to the mowing ripeness can be determined by the equation \[ E = 0.276 \sum t, \text{ mm}. \]

Based on the obtained values of bioclimatic coefficients, we have constructed biological evaporation curves for the interphase periods. It was found that the dynamics of bioclimatic coefficients reflects the biological characteristics of crop formation, coinciding with changes in the average daily water consumption of crops.
### Table 2. Bioclimatic coefficients for predicting water consumption (Kt; Kd) by interphase periods and during the vegetation of winter rye and deciduous crops in the system of three crops per year

| Interphase period | Total water consumption, mm | Duration, days | Biological need for heat, $\sum t^0$ C | The sum of air humidity deficit, gPa | Forecasting formula for total water consumption E, mm |
|-------------------|-----------------------------|---------------|-----------------------------------|-----------------------------------|--------------------------------------------------|
| **Winter rye - the first crop** | | | | | |
| Sowing- | 14,6 | 9 | 147 | 65 | $0.099 t_1$ | $0.224d_1$ |
| seedlings- | 32,1 | 21 | 282 | 142 | $0.114 t_2$ | $0.226d_2$ |
| tillering- | 27,5 | 26 | 198 | 86 | $0.139 t_3$ | $0.319d_3$ |
| Sowing- | 74,2 | 56 | 627 | 293 | $0.118 t_{1,4}$ | $0.253d_{1,3}$ |
| termination of vegetation renewal of vegetation- | 48,2 | 23 | 163 | 91 | $0.295 t_4$ | $0.530d_4$ |
| Shooting- | – | 137,6 | 23 | 367 | 270 | $0.374 t_5$ | $0.509d_5$ |
| sowing- | 260,0 | 102 | 1157 | 654 | $0.225 t_{1,5}$ | $0.398d_{1,5}$ |
| harvesting | | | | | | |
| **Corn and Sudanese grass – the second crop** | | | | | |
| Sowing-seedlings | 26,1/27,8 | 10 | 192/197 | 106/100 | $0.136/0.141 t_{1}$ | $0.246/0.252d_{1}$ |
| Seedlings | 146,4/135,0 | 24 | 636/537 | 404/400 | $0.230/0.251 t_2$ | $0.362/0.337d_2$ |
| Tillering- | 175,7/162,0 | 21 | 504/516 | 400/377 | $0.349/0.314 t_3$ | $0.439/0.430d_3$ |
| Shooting- | 49,0/48,6 | 6 | 129/136 | 96/91 | $0.380/0.357 t_4$ | $0.510/0.534d_4$ |
| Heading of panicles | 397,2/373,4 | 61 | 1462/1389 | 1002/992 | $0.272/0.269 t_{1,4}$ | $0.396/0.376d_{1,4}$ |
| **Corn mixed and sorghum - the second crop** | | | | | |
| Sowing-seedlings | 25,4 | 10 | 218 | 116 | $0.116 t_1$ | $0.219d_1$ |
| Seedlings-Tillering | 126,0 | 25 | 519 | 390 | $0.242 t_2$ | $0.323 d_2$ |
| Tillering shooting | 183,6 | 22 | 533 | 443 | $0.344 t_3$ | $0.414d_3$ |
| Shooting- | 61,3 | 7 | 164 | 136 | $0.373t_4$ | $0.450d_4$ |
| Heading of panicles | 396,3 | 63 | 1434 | 1085 | $0.276 t_{1,4}$ | $0.365d_{1,4}$ |

The maximum values of bio-climatic coefficients fall on the phases of the most intensive growth (shooting - heading of panicles), and their minimum values fall on the initial growing season (seedlings - tillering). It should be noted that the bioclimatic coefficients (Kt and Kd) in summer are significantly higher than those in spring and autumn, which indicates the seasonal variability of the
absolute values of the coefficients. Bio-climatic coefficients established by the value of the air humidity deficit (Kd), change following the temperature coefficients (Kt). At the same time, in years with different weather conditions, the Kd change more than Kt. As for the temperature regime in the dry steppe and semi-desert of the Caspian region, it remains more stable and deviations from the climatic norm are within ± 10%. Our field experiments and calculations showed that the total water consumption of annual fodder crops in single species and mixed crops during the growing season established by the calculation methods using zonal bioclimatic coefficients and normalized coefficients of total water consumption are equal (Table 3). For practical purposes, all the methods were used, but the calculation methods with temperature coefficients of the total evaporation reflect the real conditions of moisture demand more accurately.

Table 3. Comparative evaluation of methods for calculating the total water consumption of annual fodder crops under optimal soil water conditions (75-80% NM)

|                      | Kostyakov’s water balance method, $E_f$, mm | Filin’s method of normalized coefficients, $E = K_{st, Y}$ | Bioclimatic method according to G.K. Lgov, A.I. Sharov, $E = Kt \sum t$ | Bioclimatic method according to A.M. Alpatyev, S.M. Alpatyev, $E = Kd \sum d$ |
|----------------------|---------------------------------------------|----------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Oats + peas + sunflower | 366.7                                       | 372.6 (101.6)                                            | 373.0 (101.7)                                                               | 407.0 (111.0)                                                                |
|                      | 349.2                                       | 329.4 (94.3)                                             | 345.0 (98.8)                                                                | 300.2 (86.0)                                                                 |
|                      | 373.3                                       | 349.6 (93.7)                                             | 366.8 (98.2)                                                                | 390.3 (104.5)                                                                |
|                      | 363.0                                       | 350.0 (96.6)                                             | 361.6 (99.6)                                                                | 365.8 (100.8)                                                                |
| Corn + Soy           | 437.8                                       | 448.3 (102.4)                                            | 456.8 (104.3)                                                               | 444.1 (101.4)                                                                |
|                      | 451.7                                       | 433.4 (95.9)                                             | 443.9 (98.3)                                                                | 436.1 (96.5)                                                                 |
|                      | 463.2                                       | 473.3 (102.2)                                            | 442.5 (95.5)                                                                | 466.5 (100.7)                                                                |
|                      | 450.9                                       | 451.7 (100.2)                                            | 447.7 (99.3)                                                                | 448.5 (99.6)                                                                 |
| Winter rye           | 278.6                                       | 269.2 (96.6)                                             | 286.1 (102.7)                                                               | 308.3 (110.7)                                                                |
|                      | 255.2                                       | 269.3 (105.5)                                            | 278.8 (109.2)                                                               | 276.8 (108.4)                                                                |
|                      | 246.2                                       | 252.4 (102.5)                                            | 219.4 (89.1)                                                                | 195.8 (79.5)                                                                 |
|                      | 260.0                                       | 263.6 (101.4)                                            | 261.4 (100.5)                                                               | 260.3 (100.1)                                                                |
| Corn + Sudanese grass| 377.9                                       | 368.7 (97.0)                                             | 395.2 (104.5)                                                               | 393.0 (104.0)                                                                |
|                      | 391.5                                       | 408.2 (104.0)                                            | 381.9 (97.3)                                                                | 382.0 (97.3)                                                                 |
|                      | 421.2                                       | 443.9 (105.4)                                            | 415.6 (98.7)                                                                | 417.3 (99.1)                                                                 |
|                      | 397.2                                       | 406.9 (102.4)                                            | 397.6 (100.1)                                                               | 397.4 (100.0)                                                                |
| Sudanese grass (aftergrass) | 257.2                                   | 236.5 (92.0)                                             | 258.5 (100.5)                                                               | 272.9 (106.1)                                                                |
|                      | 257.9                                       | 298.9 (115.9)                                            | 252.2 (97.8)                                                                | 229.1 (88.8)                                                                 |
|                      | 270.6                                       | 276.1 (102.0)                                            | 275.0 (101.6)                                                               | 288.7 (106.7)                                                                |
|                      | 261.9                                       | 270.5 (101.9)                                            | 261.9 (101.0)                                                               | 263.6 (100.6)                                                                |

In our long-term water-balance field experiments, we obtained data that confirm that the reduced water consumption per unit yield of fodder crops with an increase in the level of crop productivity. In arid regions, the crop yield is determined by the moisture conditions; within the boundaries of optimal soil moisture, it largely depends on the level of mineral nutrition. Mathematical processing of the experimental data by the methods of correlation and regression analysis made it possible to obtain equations reflecting the dependence of the coefficients of water consumption of annual fodder crops...
on the irrigation regime and the doses of mineral fertilizers in agro-climatic and soil conditions of the Caspian lowland.

The regression equations reflect the positive relationship between the coefficient of water consumption and irrigation regimes and the inverse correlation of the coefficient of water consumption and doses of mineral fertilizers. Verification of the formulas using independent data showed a convergence of the actual and calculated values of the water consumption coefficients; differences between them did not exceed ± 10%. The normalization of the coefficients of water consumption depending on the water regime of the soil and doses of fertilizers allows us to determine the total water consumption for the planned yield on irrigated lands of the Caspian region.

Thus, the results provide an opportunity to specify and determine the values of zonal coefficients of the biological curve of evapotranspiration of annual fodder crops under dry climatic conditions in semi-desert zones of the Caspian region. In programmed sowings, the temperature coefficients of total evaporation have stable variation values within (± 10–15%). For the efficient use of water resources on irrigated fields, the specified normative coefficients of water consumption differentiated by water conditions, nutrient regimes and levels of the planned yield are of great scientific and practical importance.

4. Conclusion

For the practical use of the biological and mathematical models for controlling the water regime in programmed crops, the following algorithm was developed and tested both in experimental and production conditions: for the sowing date or the date of resumption of vegetation, the reserves of productive moisture are determined. Then, the values of the permissible deficit of water balance in the active soil layer adopted for each plant are calculated when dried to a moisture content of 75-80% HB (D) and 70 - 75% HB (D₂). The water balance deficit is predicted according to the equations of the biological and mathematical models for the corresponding interphase periods of vegetation. If there is precipitation, the calculated water balance deficit is reduced by the amount of precipitation. The next irrigation phase starts when the integral curve of the water balance deficit reaches D values, and ends at Dg. Computer calculations for each field are carried out using a short-term forecast of average daily air temperatures. Information for managing the irrigation regimes is issued 2 to 3 days before the next irrigation phase indicating its rate and completion date for each field. In the experimental production conditions of the Caspian lowland of Kalmykia, the bioclimatic method can be successfully applied using temperature coefficients of the total evapotranspiration of annual fodder crops for the operational management of the water regime of zonal soil subtypes in the arid climate.

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