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Water Balance Methodology for indirect assessment and prediction of basin water yield under human-induced land use changes

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Abstract The lastest versions of the Heat and Water Balance Models (HWBMs) are presented and their applicability to predict evapotranspiration losses from watersheds under changed land use patterns in rain-fed agriculture (crop allocation, crop yield, fertilizer application), and to predict soil moisture availability dynamics during the growing period (for plant productivity estimation) are discussed. The versions are based on the integrated "index" water balance approach which presupposes construction of nonlinear relationships between heat and water budget components under different natural and perturbed conditions (soil type, groundwater table position and salinity, plant species and productivity, etc.) using the multidimensional cubic spline technique. The examples on application of the methodology to different conditions are cited for several regions (Middle and Lower Volga River basin, piedmont and lowland parts of the North Caucassian economic region). A comparison is made of the models with several mechanistic heat and water balance models, and combination techniques. The advantages and shortcomings of the models under analysis in respect of their accuracy and practical applicability are highlighted.

Key words evapotranspiration; HWBM; soil moisture regime; Volga River; water balance

BACKGROUND

With respect to the scale-dependent prediction of man-induced changes in basin water yield, there is a strong demand for studies, not only into river runoff itself, but into runoff generation processes and catchment modelling, since both quantity and quality of surface and groundwater resources depend largely on interaction between surface runoff, soil and groundwater. During the last decades, much has been learned about runoff generation processes and flows along different pathways, especially at hillslope to small catchments scales. Innovation using remotely sensed data, tracer and new hydrometric approaches, and GIS-based computation techniques greatly contributed to a more realistic representation of the underlying mechanisms within process-oriented rainfall–runoff models at the meso and macroscale, and to providing descriptions of the models and their updating procedures in a standard format for disseminating them to all concerned parties.

Modern hydrological models of the distributed system type subdivide drainage basins into a lot of area elements of different scales: the regional climatological scale and different hydrological scales—the choric ones (drainage basin or sub-basin, polygon, runoff forming complex) and the topic ones (sites, plots, hydropedotopes, ecotopes, flow strips, elementary areas, hillslope catenas, hydrological response unit, etc.). For the latter, Water Balance Models (WBMs) usually calculate one-dimensional heat and water fluxes with a high temporal resolution, predominately using the statements of thermodynamics of moist air and semi-empirical theory of turbulence. The regionalization and upscaling may be achieved by different methods: using derivation of location-independent statistical distributions of representative real and "theoretical" elementary areas; by the introduction of the "effective" parameters, by hydrological similarity analysis or aggregation; by scale-dependent pre-processing of input data sets (Dyck, 1985; Vinogradov, 1987; Kavvas, 1989; Wood, 1995; Kalma & Sivaparan, 1995; Diekkruger *et al*., 1999). Nevertheless, the usefulness of the models as instruments for predicting the impact of man-induced climate and land-use changes remains questionable, due to a range of peculiarities of the hydrological cycle transformations, both within the spatial and temporal domains.

Within the spatial domain, the errors may arise from disregarding the dependencies among soil type, surface slope and aspect, and land use. In a majority of hydrological models, the area elements are considered as natural associations of geology, geomorphology and soils. Vegetation cover can also be derived from general thematic and special schematic maps, and by remote sensing. But the land use information from the latter is classified, usually into very rough classes (urban areas, coniferous forest, deciduous forest, lakes, grassland, agricultural areas), although a more differentiated picture is required. For example, the crop models, to be included into the general catchment models, at least require characteristics such as plant type, plant age and height, nutrients, fertilizer or pesticides availability, to be able to calculate evapotranspiration losses with desirable accuracy. In real watersheds, the spatial inconsistency is usually being observed between natural land surface elementary units and the land use patterns. The latter depends to a large extent on socio-historical conditions and on economic considerations that can cause additional problems to the interpretation of land use maps and images for hydrological modelling.

Within the temporal domain, no less great difficulties exist due to the necessity to incorporate interactions between the rates of land-use changes and degradation processes and the changing soil and vegetation environment responding to both the degradation and external forcing (climate). There exist several approaches in progress, which incorporate the dynamic interactions to simulate possible scenarios over periods of several decades, and to provide some forecasts of the impact of alternative policy options in different natural conditions (Kirkby *et al*., 1996; Rodda *et al*., 1996; etc.). The most significant advances of the approaches consist in using mainly publicly available data in the development of hydrological models within Decision Support Systems (DSS), in order to be able to present results which can be used directly by policy makers and managers, and in making the DSS an adaptable tool, with the ability to incorporate additional models when they become available.

But in a majority of hydrological models the runs are carried out using time-independent soil and vegetation conditions since the advantages, in simplicity, are thought to outweigh the rather slight advantages of accounting for the relatively small man-induced water balance transformations, compared to the uncertainty of rainfall–runoff modelling at the larger scales. At micro and mesoscales, the impact of the transformations may be rather significant, but the difficulties of model calibration remain, because to specify the land use of agricultural areas, the statistics at the county or district level should be used but usually no spatial data allocation is available, only percentile data that need an extensive pre-processing effort under the modern crop rotation practice. Due to the uncertainties and inevitable assumptions and speculations, most models of river hydrology remain conceptual and "semi-quantitative". They usually include modules of "black-box" or "grey-box" type.

Now the tendency is being observed to larger abstractions and to simplification of the model structure. In that approach, the within-basin areas, which are particularly important, are modelled in detail, whereas the less important ones are lumped together by a simplified statistical approach. The calculation of the input parameters for various consolidated areas takes place by weighting them so that dominant basin or regional structures are emphasized. At the present time, the approach seems promising, bearing in mind the necessity to join the very different paradigms of disciplines associated with the environmental domain, and those of social, economic and management disciplines, which can be characterized by holistic and problem-solving modes of thought aimed at directly influencing policy and practice. At present, the vulnerability of economic systems is furthermore strengthened due to the set in of the "epoch of limits", i.e. the situation when effectiveness of human activities in the production sphere is being limited by natural potentials and therefore, the systems are more sensitive to natural perturbations. In general, the problem resolves itself into "making better use of what exists" in all spheres of human activity. In a number of the most advanced studies into natural, semi-natural and artificial environmental objects, the role of humans in their functioning and effectiveness is considered, and development of knowledge is focused on creation of sufficiently rigorous and relatively easy-to-use applied models which do not break down in the absence of an inordinate high degree of site-specific information. The main emphasis is on "subject–object" interactive methodology based on Information Society Technologies, on individualization (personalization) of research, and on wide participation of experts, decision makers and all other concerned parties in the knowledge development.

METHODOLOGY

The Water Balance Models (WBMs) this paper deals with, may be qualified as deterministic ones based on the macroscopic version of the equation of continuity when heterogeneous processes of the hydrological cycle are lumped over finite time intervals and areas, and related by the general equation:

$$P + R_{si} + R_{ui} = E + R_{so} + R_{uo} + R_s + R_g + \Delta S + \eta \tag{1}$$

where P is precipitation; E is actual evapotranspiration; R_{si}, R_{ui} are net surface and subterranean natural and man-induced water diversions from other basins; R_{so}, R_{uo} are net surface and groundwater natural and man-induced transfer to other basins; R_s, R_g are surface and subterranean runoff; ΔS is change in total storage; η is an error term. Various versions of the equation exist since at different scales the importance of different hydrological cycle processes may change significantly. The modelling usually concentrates on the most important processes and on the appropriate representation of them, and depends on current understanding of physical and other processes, on the data available and the purpose chosen, so there is no WBM which is suitable for the whole range.

The central idea of the water balance methodology is to avoid difficulties regarding the inadequate process understanding both at finer and at coarser scales and the specific problems of upscaling, through fulfilment of analysis and linking balances for different basin zones and separate water objects, in order to reveal systematic errors and miscalculations in the components' determination, and to define the values of separate non-explored components (as residual terms). The latter is of great importance, since with the exception of river runoff, which is an integrated measurement, for all the water balance components, the problem of areal representation of point measurements exists, and a majority of methods for their determination have been developed using findings of the "site science" (Andreyanov, 1977; Penkova, 1984; Dyck, 1985). For example, the mass calculations of water balance for small and medium size watersheds in the Middle Volga region, even within the well nested models, have shown that η–values may be comparable to the balance components (Table 1). In this case, the three store WBM for small river basins was under examination:

$$P + R_{si} = E_p + R_s + \Delta S_s + I_a \quad (2)$$

$$I_a = E_w + \Delta S_a + I_g \quad (3)$$

$$I_g + R_{ui} = E_g + R_g + \Delta S_g \quad (4)$$

where E_p, E_w are evapotranspiration from surface zone of basin and from vadose zone; ΔS_s, ΔS_a, ΔS_g are change in surface water storage (in snow cover, glaciers, in local depression areas, in lakes and reservoirs, in stream channels), change in water storage in vadoze and saturation zones; I_a, I_g are filtration into vadose zone and groundwater recharge (Andreyanov, 1977; Penkova, 1984). The P, E_p, E_w, R_{si}, R_{ui}, R_s, R_g, ΔS_s, ΔS_a, ΔS_g-values are determined independently, I_a, I_g and η – as residual terms for a conformable zone.

Table 1 Seasonal water balance for the Middle Volga basins, mm (March–May, 1975).

Basin number	Catchment area	P	R_s	R_g	E	ΔS_s	ΔS_a	ΔS_g	η
1. B.Kokshaga–Grishkino	5750	94.1	66.9	13.6	188.1	–100.0	–82.8	10.3	–9.2
2. Kazanka–B.Derbyshki	2370	74.4	71.5	12.5	130.7	–76.0	–104.3	40.0	–29.3
3. Samara–Yelshanka	22800	64.4	12.9	8.3	138.2	–114.0	19.0	0.0	47.9
4. Chapayevka–Mikhaylovka	1480	59.7	10.0	2.3	145.5	–101.0	–1.6	4.5	11.1
5. Tereshka–Kurilovka	7180	48.4	13.6	8.7	148.6	–167.0	40.5	4.0	76.5
6. B.Uzen–M.Uzen	3930	39.5	0.0	0.0	139.8	–38.0	–66.3	4.0	–18.5

According to the most generalized classification, the WBMs may be qualified as system models belonging to the "grey box" structural form, i.e. the intermediate one between the "black box" ones with multiple inputs and a single output (river runoff), and the mechanistic models with defined intrinsic model structure. In the basin WBMs, usually the structure of the basin body (or its part) and the structure of the water cycle processes are discerned. In part these structures correspond to each other in a definite manner. For example, a term such as inflow refers to a part of the vadose zone above the first impermeable layer, while the baseflow is usually the saturated zone. It is possible to speak about compliance between the spatial structure of precipitation and evaporation fields, as well as of other components, and the basin structure (dependence of the hydrological cycle process on morphography and geology). But the intrinsic structures are proved in the spatio-temporal distribution of the water cycle elements (including diurnal, seasonal and multi-annual cycles).

Distinctive features of evapotranspiration connected with functioning of vegetation cover exist, namely separation of *E*-values into transpiration and physical evaporation from surface, vadose and saturation zones. The structuring of the *E*-process is of special interest to vegetation science, agricultural and ecological disciplines. As a whole, botanists and plant physiologists tend to overestimate the significance of transpiration in processes of a landscape functioning, and to underestimate the physical evaporation. In most investigations, the latter is not assessed at all. On the other hand, in applied land reclamation science, in climatology and hydrology the opposite situation observed. In most climatological and hydrological models, the process of evapotranspiration tends to be considered as a mechanistic process, the intensity of which is conditioned by the intensity of radiative heat and water budgets in plants and in surrounding space. There are many mechanistic models for the plant cover, the kernels of which consist in basic mass and energy diffusion and transfer relations. But usually they are too detailed and data extensive, which hampers their applicability to practice.

One should concur with opinion that there is a gulf between researchers and practicians within modelling of natural systems. In most applied models, which are used in practical climatology, hydrology and land reclamation sciences, *E* is assumed proportional to the current relative water content in the root zone, between zero-value at wilting point, and some value of optimal content, between which both the largest (energy-limited) *E*-values, and the greatest plant productivity are observed. In the models for irrigation rates, *E* is calculated within the optimal diapason of soil water content W, and the influence of plant type is accounted using "crop growth stage coefficients" and "biological parameters" which change over "biological curves" (Alpatjyev, 1974; Dorenboth & Pruitt, 1975, etc.). For example, in the SHI model (Kharchenko, 1975) the "biological parameter" β is used, the values of which vary from 0.8 to 1.2, in the phases of active growth. The relative soil saturation γ is calculated as a fraction of field capacity W_f ($E = \beta \times E_0 \times \gamma$, where E_0 is potential evapotranspiration). The lower optimum (W_l) is equated with about $0.65W_f$. Below the latter, *E* is assumed to be the linear function of $\gamma = W/W_f$.

Such a relationship was first suggested by M. I. Budyko and was based on results of laboratory experiments, i.e. under the absence of precipitation. For field conditions Budyko suggested the substitution of W_f by "critical water content" W_0 under and above which *E* is equal to E_0. The W_0-values were determined from evapotranspiration data recorded by soil evaporimeters on grasslands, and generalized over natural zones for applied climatological computations (Budyko, 1971). Later on, the linear relation for evapotranspiration efficiency $E/E_0 = f(W/W_f)$ was called into question in a number of works. However, it still is considered basic in most theoretical and applied methods and techniques.

Latterly, the main directions for process studies were forced by finding much more significant variation for "biological" parameters. SHI experimental data from irrigated fields in the Lower Don basin showed that the β-values differ by a factor of four or more from those recommended in Kharchenko's method. For perennial herbs in the Middle Volga District, the β-values of 100-fold and more excess were found (Penkova, 1980). The main reason for the differences was the non-accounting of the structure of E (the partitioning of E into the fast physical evaporation of intercepted precipitation and the evapotranspiration from soil). It became evident that the existing models should have been extended with regard to this factor. The problem was especially topical to rain-fed agriculture in the drought-prone "granaries" of the country located in the Middle and Lower Volga and in Caucassian economic regions. Besides, the existing techniques did not allow for important factors of cropping such as agrotechnics (fertilizer, pesticides, type of irrigation system, crop varieties and productivity, etc.) that restrained their applicability, both for planning of the growing plant development and for assessment of impact of the development on water resources and water availability. For the latter, due to non-sufficient development of complex hydrological modelling, the indirect water balance methodology was recommended which uses the differential correlation for basic WBM-components:

$$\Delta R = \Delta S + \Delta E \tag{5}$$

The methodology presupposes determining the ΔS and ΔE-values for a variety of surfaces and water bodies within a river basin (crops, grasslands, wetlands, forests, lakes and reservoirs, etc.). It was only seen as acceptable for relatively small land use impacts, but it requires that specific methods for water balance components have to be developed, together with the methods for scaling (weighting) the results and methods for assessment of the direct withdrawals (water intake for irrigation and water-supply development in arid lands, for population and industry need, partial runoff diversions among basins, etc.) (Shiklomanov, 1986, 1989; Voskresensky, 1986; Penkova & Shiklomanov, 1996, 1998).

As distinct from the techniques which use regionalization indices based on physics and mathematics, the indices used in ecology and soil science (water available for plants, height of capillary flux, nutrient and contaminant concentrations in soil and groundwater, etc.), and the alternative approach of explicitly nesting models for different semi-natural (uncultivated vegetation) and cultural ecosystems are used within the methodology. As the elementary units, the biogeocenotic scale ecosystems are considered since at this level the management options are usually applied in practice. Within the biogeocenoses, the scale invariant processes structure is assumed with the same processes acting in their different parts. Unlike the hydrological models, where hillslope flows are then routed through the channel network, each ecosystem is assumed to be connected with the drainage network (that nonetheless has to be proved from mean ecosystem size chosen and the mean drainage density). Among others, the aspects of spatial transference of weather data, especially variability of air humidity and precipitation, and the thresholds in catchment size, are found to be of major importance. The thresholds' determination should consist of classification of river basins for the given region according to runoff formation mechanisms: prevailence of direct surface flows or subterranean ones (inflow, baseflow), in conformity with morphogenetic and geological conditions. Formal procedures for the classification, besides the comparative–descriptive analysis, are to be based on traditional regional runoff–catchment area relations, and on the information technologies. Among the latter, the digital multi-level hydrological mapping based on ordering river basins according to the Horton-Strahler model is recommended (Penkova & Kolpakova, 1997).

The restored runoff-values should be used in both techniques

Several approaches to explicitly determine the evaporation of intercepted precipitation exist (Budagovsky, 1964; Bulavko, 1971; Andreyanov, 1977; Eagleson, 1978; Penkova, 1978, etc.). From a physical basis, the process is usually described using the equation:

$$E_p = E_0 * \exp(-\alpha t) \qquad (6)$$

where α is a coefficient of declining E_p over time t. Because the equation cannot be solved due to data constraints, for practical applications the simpler relations have been suggested. For example, in monthly water balance calculations Bulavko (1977) suggests equating E_p to potentially possible monthly interception (ΣP_p) calculated as:

$$\Sigma P_p = P_p \times N + \Sigma P_{N<1.0} \qquad (7)$$

where N is number of days with precipitation less than P_p, the maximum value of interception during each rainfall event (1.0 mm); $P_{N<1.0}$, sum of daily precipitation less than P_p. The technique is not used in practice due to the subjectivity of setting P_p.

In a number of works the determination of E_p is suggested on the basis of comparing daily sums of E_0 and P. For example, Andreyanov (1977) suggests calculating E for periods of several days (decade, month) as:

$$E = (E_0 - E_p) \times W/W_f + E_p \qquad (8)$$

where $E_p = \sum^{n_1-n_2} P(< E_0) + \sum^{n_2} E_0(< P)$; n_1, n_2 – number of days when $P < E_0$, and days when $E_0 < P$. The latter approach is widely used in modern hydrological modelling, but it should be qualified as high speculative, in view of uncertainty of the E_0 calculated using normally available weather data. The diurnal E_0-values normally do not reflect its values during the E_p-process, since the latter usually proceeds rapidly. Special observations show, for example, that the average time needed for evaporation from vegetation and land surface under sprinkler irrigation is close to 1–2 hours.

Other uncertainties concerning the E_0 term are connected with techniques used for its determination. There is no uniform definition for the E_0-parameter. In different works the E_0 is defined as the evaporation from open water surfaces or as evapotranspiration from a full plant cover, sufficiently moistened on a large scale, under current meteorological conditions. But the latter can not be determined from the normally recorded data. They need *in situ* measurements with high temporal resolution. The spatial resolution of data sets is of no less importance, since the E_0-values for moist areas of unlimited size can not be inferred from environmental conditions normally present over land (patchy areas of moist and dry surface) that induces the increase in E_0, despite a general decrease of the radiative balance. So, the E_0-term for almost all cases in practice, should be considered as an index, which more or less correctly reflects the evaporative demand of the atmosphere. Other parameters of modern heat and water budget techniques for evapotranspiration also cannot be determined with certainty using the available data. For example, because of nonlinear relationships between different variables of the Penman-Monteith equation, it is not correct to average the meteorological data over a day. If the sub-models for response of vegetation resistance to environmental conditions are to be biologically realistic, the time interval should not be greater than one hour. In other cases, the resistance should be determined over the same period (Stewart, 1989).

These circumstances force the renunciation of the calculation schemes of additive type like (7) and (8), and force a search for more general approaches. Within the water balance methodology under discussion, the possibility was investigated to construct integral semi-empirical sub-models for "biological" and other parameters of the Budyko-Kharchenko combined method. The study was carried out using a state composite water balance and agrometeorological network data (>100 stations) where evapotranspiration from crops and semi-natural grasslands is being measured by soil surface evaporimeters. The main idea of the approach chosen consisted in the assumption that the theory of the processes of study is known in general features, and calculation errors mainly depend on the accuracy of parameter determination. This is due to several data constraints which do not allow the application of more explicit approaches to modelling. Among the constraints one should point out the separation of the soil body from its environment and several spatial and temporal inconsistencies. In some cases, the weather gauges are not located adjacent to experimental fields (at 10 m to 10 km distance), insufficient long periods and insufficient time resolution (the calendar 10-day step) and lack of coincidence between the date of weather record and both plant growth stages and management options (fertilizer application, hay harvest, etc.) are being observed, as well as in complete sets of measurements realized (lack of groundwater table and hydrochemical data), etc. The main task was to reconcile the integrated coarse scale sub-models with the process understanding at a finer scale.

RESULTS AND DISCUSSION

Surprizingly, the results obtained are good. They not merely confirm several theoretical ideas of the evapotranspiration process, but they have the inherent theoretical advantage over existing mechanistic approaches. As an example, several graphic relationships constructed using cubic splines are presented in Figs 1 and 2 for different natural conditions. The diagrams in Fig. 1 demonstrate that under very low yield, the increasing mineral nutrition corresponds to a considerable increase in total evaporation, for average yield (15 to 30–40 c ha^{-1}) increasing β is characterized by saturation at different levels of V_f, and under high productivity of 60 c ha^{-1} and above evapotranspiration is steadily lowered with V_f which is in good agreement with existing notions about water exchange processes in rain-fed agriculture. In Fig. 2, the relationships between *Cd* and *D*-parameters, groundwater table (Hgr, m) and Cl-ion concentration in groundwater (mg L^{-1}) are presented which are obtained using Heat and Water Balance Model (HWBM, equations (9)–(11)) for *Poa bulbosa* (*Poa pratensis*) plots of light soil texture, under fixed P and relative soil saturation (W_b/W_f-values), and the comparison of measured and calculated Cd and W_e:

$$E = Cd \times E_0*[(W_b + W_e)/2/W_f] \quad (9)$$

$$W_e = [W_b*(1 - Cd \times E_0/2W_f) + P + D]/(1 + Cd \times E_0/2W_f) \quad (10)$$

$$D = E + W_e - W_b - P = K_g - I_g - R_s + \mathrm{d}E + \mathrm{d}P + \mathrm{d}W + \eta \quad (11)$$

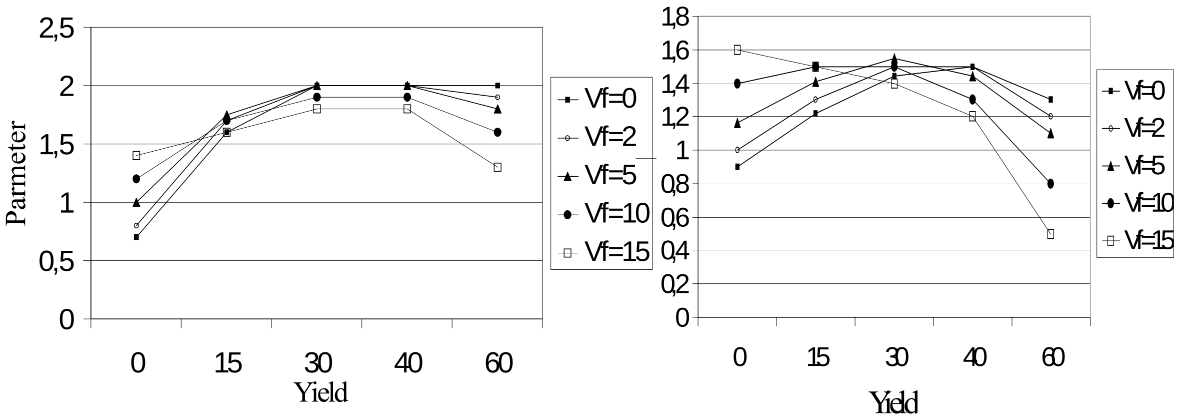

Fig. 1 Effects of fertilizers use (V_f, metric centner ha^{-1}) and economic crop yield (metric centner ha^{-1})on β–parameter under mean soil water content. Winter wheat, Northern Caucasus, Russia, June, P = 20 mm. Left – Hgr = 5 m; right – Hgr = 30 m.

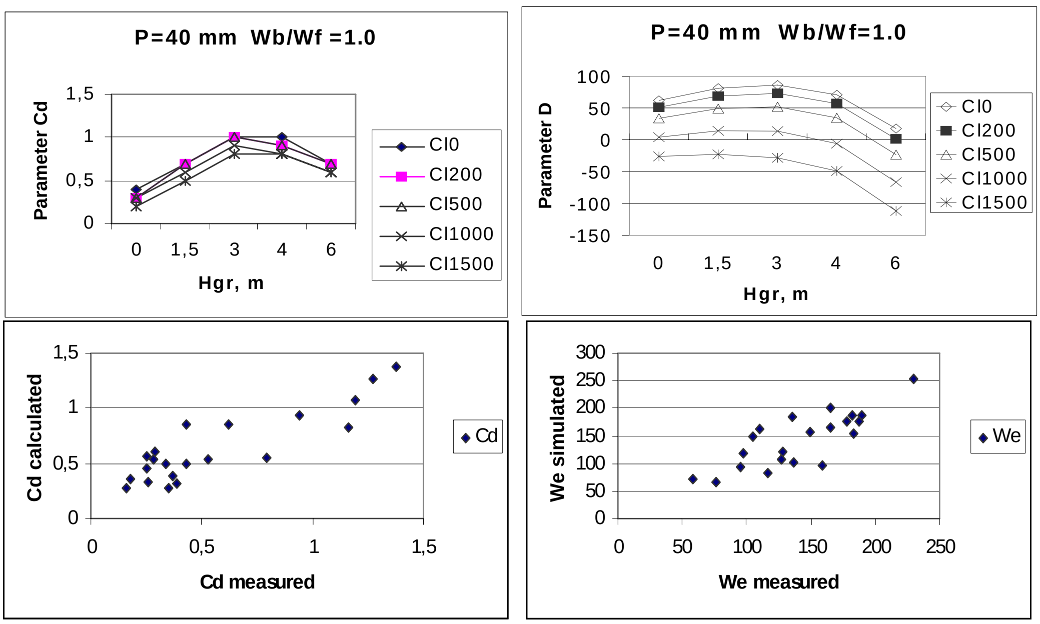

Fig. 2 Dependencies of Cd and D-parameters on groundwater table depth and Cl-ion concentration for the month before the flowering date. Lower Volga District.

where W_b, W_e are productive soil water content at the beginning and end of the calculation period (mm); *Cd* is structural-dynamic parameter-function analogous to β-parameter; *D* is "total error" (mm). *Cd*-values obtained from rearranged equation (9), and *D*-values that include elements of water exchange of active soil layer (K_g, I_g), measurements errors (d*E*, d*P*, d*W*), and non-accounted delivery of moisture (η) (precipitation intercepted by plants, dew, adsorption of moisture by plants, etc.), both are complex nonlinear functions of environment and plant physiology factors. The graphs corroborate several important features of the composite groundwater–soil–plant–atmosphere system: influence of groundwater depth on plant water intake (*Cd*-changes), transformation of water exchange in vadose zone (increasing of negative *D*-values with Hgr lowering due to deep percolation), and influence of chemical composition of shallow groundwater.

Numerous HWBMs runs for simulation of interannual soil moisture regime, showed that the semi-empirical models under development are highly sensitive and sufficiently rigorous. They enable the ecosystem (biogeocenosis, crop field) to be considered as an active component of the hydrometeorological system in an integrative manner, with generalization at a higher level of abstraction than the physical one, and giving the same status both to natural-climatic and anthropogenic (agrotechnology, irrigation, etc.) factors which are working in a feedback regime. The models may be recommended for incorporation into both the WBMs and into modern hydrological models of the distributed system type. Further differentiations are now being investigated to take account of combinations of a wider range of possible natural-climatic and man-induced conditions for plant functioning, including hypothetical cases. The investigations are being fulfilled within the DSS-packages in order to incorporate additional models when they become available (including agricultural economics models which are equally important to improve land and water management in terms of a financial cost to the farmer and a cleaner environment).

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