



Spatial distribution of soil moisture content within catchments and its modelling on the basis of topographic data

A.A. Svetlitchnyi*, S.V. Plotnitskiy, O.Yu. Stepovaya

Department of Physical Geography, Odessa National I.I. Mechnikov University, Shampansky per., 2, 65058 Odessa, Ukraine

Received 30 November 2001; accepted 12 February 2003

Abstract

This paper deals with the development of a model of the average seasonal spatial distribution of soil moisture content on slopes or in small catchments. The model is based on a quantitative assessment of the water and heat balances of the upper soil layer under different climatic conditions and a generalization of the field data by Romanova [Climate of Soil, Hydrometeorizdat, Leningrad (1971) 39]. The ratio of soil moisture on a sloping surface and that on a flat surface is related to slope aspect by trigonometric (Fourier) series. The model estimates the average spatial distribution of relative moisture content (K_w) in the upper 50 cm layer of the soil in summer as a function of the form of the relief (flat, slope), longitudinal slope profile shape (straight, concave or convex), aspect of the slope (degrees), slope gradient (dimensionless) and relative distance from the divide, which are found from a digital elevation model. The model is applicable to humid and moderately dry climate conditions. Computer simulation is performed assisted by the GIS package PCRaster (Utrecht University, the Netherlands). The test of the model was carried out using seven years (1981–1987) soil moisture data at 38 points situated within three small experimental catchments of the Boguslav Field Experimental Hydrological Base of the Ukrainian Research Hydrometeorological Institute (Kiev region, Ukraine).

© 2003 Published by Elsevier Science B.V.

Keywords: Soil moisture content; Spatial distribution; Modelling; Topography; Digital elevation model; GIS technology

1. Introduction

The distinctive spatial variability of soil moisture has been known for a long ago (Izmailsky, 1894). Romanova (1977) remarks that the soil moisture in different locations of slopes differs even more than it happens under transition from one climatic zone to another: the moisture of the soil on the top of a hill and in the upper part of a slope in the humid zone can be

less than that at the foot of a hill in a drier zone. Estimating soil moisture for different locations is needed for solving a broad spectrum of tasks connected with the usage and protection of soils, water and other kinds of natural resources.

The problem of spatial soil moisture content variability was investigated by Silvestrov (1955), Fedoseev (1959), Fishman (1968), Shvebs (1968), Shipulin (1973), Mazur (1975), Romanova (1977), Romanova et al. (1983), Hawley (1983), Burt and Butcher (1985), Fitzjohn et al. (1998), Western et al. (1998), Naden et al. (2000) and by other scientists.

* Corresponding author. Tel.: +380-482-687886.

E-mail address: svetl@te.net.ua (A.A. Svetlitchnyi).

97 But while analysing the results we came to the
 98 conclusion that there is no sufficient clearness in
 99 the given problem even nowadays. To a great extent
 100 the lack of clarity connected to the fact that the field
 101 measurements of soil moisture content in terms of its
 102 spatial dynamics are a very labour-consuming job and
 103 these field measurements are not included in the
 104 observation programs of meteorological or hydro-
 105 logical stations and they have irregular character.
 106 Taking into consideration that the results of these
 107 observations depend on many factors there was and
 108 there is a problem with interpretation of limited
 109 amounts of these data. Moreover, the absence of
 110 suitable technologies for analysis and evaluation of
 111 spatially distributed physical variables restricted the
 112 development of adequate methods of the calculation
 113 of the spatial distribution of soil moisture content on
 114 the basis of available data for a long time.

115 It is known that the spatial distribution of moisture
 116 content of the upper layer of the soil has a complex
 117 character, which depends on natural and anthropo-
 118 genic factors. The character of the natural distribution
 119 of soil moisture (which does not relate to human
 120 activity) mainly depends on relief. Relief determines
 121 the redistribution of solid precipitation both as a result
 122 of blizzard shift and under the influence of insolation,
 123 causing spatial differences in the depth and density of
 124 snow cover, in the intensity of snow melting and
 125 surface runoff as well as in the intensity of total
 126 evaporation which determine the decrease of soil
 127 moisture between rainy periods. If one takes into
 128 account that the spatial distribution of such charac-
 129 teristics of the topsoil layer as water-absorbing and
 130 water-retaining abilities are determined mostly by the
 131 relief (Furley, 1971; Gerrard, 1981), it becomes clear,
 132 that the role of the relief in the spatial distribution of
 133 soil moisture content increases even more.

134 Among the factors of economic activity that affect
 135 the spatial distribution of soil moisture content within
 136 catchments the most important role is played by the
 137 types of agricultural crops and the character of their
 138 alternation (in crop rotations) as well as the technol-
 139 ogy of crop cultivation. Although the effect of these
 140 factors is rather considerable, nevertheless it is
 141 secondary, because it takes place against the back-
 142 ground of atmospheric precipitation occurring under
 143 the influence of relief caused factors. May be due to
 144 the 'primacy' of a relief influence on the spatial soil

moisture distribution and the necessity of a quantitat- 145
 ive evaluation of this influence when solving different 146
 tasks, most studies (Silvestrov, 1955; Shpak, 1964; 147
 Shvebs, 1968; Furley, 1971; Mazur, 1975; Romanova, 148
 1977; Romanova et al., 1983; Hawley et al., 1983; 149
 Burt and Butcher, 1985; Naden et al., 2000) have 150
 focused on establishing a dependency between 151
 different relief factors, mainly aspect, gradient and 152
 shape of the slope profile, and soil moisture or relative 153
 indexes of soil moisture. 154
 155

2. Method 156

157
 158
 159 Based on an analysis of methods of soil moisture
 estimation at different locations we believe that one of
 the best methods is the method developed by
 Romanova (1966, 1971). The main idea of this
 method is the redistribution of summer precipitation
 as surface runoff, and accounting for differences in the
 radiation regime of inclined surfaces (Kondratjev and
 Monolova, 1961; Golubeva, 1967). On this basis,
 Romanova (1966, 1971) estimated the average
 seasonal moisture content of the top half-meter layer
 of soils at various sites of slopes as a function of the
 form of relief (type of a slope, slope gradient, length
 and aspect) and soil type. Calculations were made on
 the basis of the equation of water balance of a half-
 meter layer of soil, taking into account atmospheric
 precipitation, surface runoff and evaporation. It was
 assumed, that no water flow deeper than active layer
 of soil (0.5 m) occurred. Results of the calculations
 for spring, summer and autumn were generalized for
 two types of a longitudinal slope profile—(a) direct
 and concave and (b) convex and for six wetness
 zones—from very wet to dry and are given as
 diagrams. The wetness zones were allocated in
 accordance with average long-term values of soil
 moisture (W) (in percentage of its water capacity
 (WC)) and a ratio between evaporation (E) and
 evaporative capacity (EC). In particular, for the very
 wet zone $W \approx 70\text{--}90\%WC$, and $E/EC \approx 0.7$, for the
 dry zone $W < 20\%WC$, and $E/EC < 0.3$. 187

188 Table 1 gives the values of the relative 'wetness
 coefficient' (K_w), i.e. the ratio of soil moisture on a
 slope and soil moisture on a flat surface with the
 same type of soil and vegetation for four aspects—
 North, South, East and West and for four slope 192

Table 1

Relative values of moisture content in the upper soil layer (the K_W coefficient) depending on slope profile shape, aspect and position on a slope for the summer period and humid and moderately dry climate conditions (Romanova, 1971, 1977)

Relief elements	Convex slope				Straight or concave slope			
	Aspect North	East	South	West	Aspect North	East	South	West
Flat surface	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Upper part of a slope	1.10	1.10	0.95	0.95	1.00	0.83	0.56	0.61
Middle part of a slope	1.00	1.00	0.79	0.79	1.00	1.00	0.80	0.80
Lower part of a slope	1.00	1.00	0.63	0.66	1.17	1.17	1.00	1.00
Foot of a slope	1.50	1.50	1.24	1.24	1.61	1.61	1.30	1.30

parts—upper, middle, lower and the foot of a slope for summer period of the year. The value of the K_W coefficient has been derived from the diagram developed by Romanova (1971, 1977) for climatic conditions of wetness zones II (humid) and III (moderately dry) which cover the central and the northern regions of Ukraine and also significant territories of Eastern and Western Europe. Within these zones the average annual soil moisture ranges from 40 to 70% of its water capacity, and the ratio of evaporation to potential evaporation is equal to 0.6–0.7. According to the data, presented in Table 1, on the straight or concave slopes the soil moisture increases with the distance from the divide except for the upper part of the slopes, where there is some reduction of the soil moisture downslope. On the convex slopes the changes of soil moisture with the distance from the divide are more complex because of the influence of terrain aspect. Thus, the K_W coefficient for various sites of slopes changes rather dramatically, from 0.56 to 1.50.

The Romanova method well corresponds both to modern representations about influence of various relief factors on spatial distribution of the soil moisture, and to approaches to study of this influence as a whole. So, according to Florinsky et al. (2002) in soil studies with digital terrain modelling, there is a need to take into account four types of variability in relations between soil and a relief: regional, time, depth, and scale. The seasonal nature of geostatistical structure of spatial soil moisture patterns is marked also by Western et al. (1998) and others. The developed model quite

meets to these representations. The model is developed and is recommended for application in the certain climatic (humid and moderately dry) conditions and this imposes on it quite certain regional restrictions. It allows to carry out an estimation of many years average distribution of the soil moisture during the summer period only (temporal restrictions) in the top half-meter layer of the soil (depth restriction) on slopes or in small catchments (scale restriction). However, absence among input parameters of diagrams and tables similar to Table 1 of the parameter describing the influence of declivity of slopes doesn't allow to take into account the influence of this important factor of soil moisture spatial distribution and, of course, it reduces the accuracy of its simulation. The influence of slope declivity on the soil moisture content distribution is rather effective. With an increase of the slope declivity there increases the velocity of surface water flow during spring snow melting and rainfall runoff. Because of this there decreases the time of removal of water, accumulated on the slope, and as the result, decreases the quantity of water absorbed by the soil. However, as the volume of water accumulated at the slope by the end of rainfall or snow melting is as a rule insignificant comparing with the reserve of water in the active soil layer, the difference in water income into the soil during the recession time of flow on slopes of different gradients is relatively insignificant. That is why for summer period, which is being under consideration in this article, all these factors can be left aside. At this time of the year the inequality of soil moisture

289 expenditure as a result of evaporation is the most
290 significant component for the spatial distribution of
291 soil moisture.

292 In order to account for the affect of terrain slope on
293 evaporation and hence soil moisture we added the
294 factor K_a , founding on studies

$$295 K_a = (1 - k_e \alpha) / (1 - k_e \alpha_0), \quad (1)$$

296 where α is the slope angle (degrees); α_0 is an average
297 slope angle ($\alpha_0 = 7.5^\circ$); k_e is a coefficient dependent
298 on the aspect (for northern aspect $k_e = -0.01$, for
299 eastern aspect $k_e = 0.002$; for southern aspect
300 $k_e = 0.005$, and for western aspect $k_e = -0.003$
301 (Romanova, 1971)).

302 3. Model of the spatial distribution of soil moisture 303 related to relief

304 The general regularity of the wetness coefficient
305 values changing in accordance with the slope
306 profile shape, slope aspect, distance from the divide
307 (Table 1) and slope gradient (1) facilitate the
308 computer-assisted mapping of soil moisture on
309 the basis of GIS technology. To their end,
310 the dependence of the wetness coefficient on
311 determining factors needs to be approximated by
312 functions.

313 Given the periodicity in soil moisture
314 dependence on aspect a trigonometric (Fourier)
315 series are the best for this purpose (Korn and Korn,
316 1968)

$$317 f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos nx + b_n \sin nx), \quad (2)$$

318 where $f(x)$ is some periodic function of x ; a_n , b_n
319 are the coefficients of the series which can be
320 determined from the formula of Euler–Fourier;
321 $a_0/2$ is the absolute term.

322 By applying Eq. (2) to the data in Table 1, the
323 following analytical model of the wetness coefficient
324 K_W of an active soil layer is obtained. For slopes of
325 straight and concave shapes the dependence of the
326 wetness coefficient on the distance from the divide

and aspect is obtained as

$$327 K_W = (a + 0.16 \cos A + 0.09 \sin A) K_a, \quad (3)$$

$$328 a = \begin{cases} 1 - 0.2(l/l_{\max})^{0.5}, & \text{if } 0 < l/l_{\max} \leq 0.167, \\ 0.77 + 0.43(l/l_{\max})^{1.47}, & \text{if } 0.167 < l/l_{\max} \leq 0.833, \\ 0.77 + 0.70(l/l_{\max})^{4.0}, & \text{if } 0.833 < l/l_{\max} \leq 1.0, \end{cases}$$

329 where K_W is the wetness coefficient (dimensionless); l
330 is the distance from the divide (m); l_{\max} is the overall
331 length of a slope (m); A is the slope aspect (degrees).

332 The average error of approximation of the data in
333 Table 1 by the model (3) and (4) for straight and
334 concave slopes is ± 0.05 or $\pm 4.9\%$ of the average
335 wetness coefficient K_W value.

336 For slopes of convex shape an analytical model of
337 the following type is obtained:

$$338 K_W = (b + 0.14 \cos A + 0.10 \sin A - 0.02 \cos 2A) K_a, \quad (5)$$

$$339 b = \begin{cases} 1.04 - 0.22(l/l_{\max})^{0.93}, & \text{if } 0 < l/l_{\max} \leq 0.833 \\ (0.86 + 18.0(l/l_{\max} - 0.833)^{2.0}), & \text{if } 0.833 < l/l_{\max} \leq 1.0. \end{cases}$$

340 The average error of approximation of the data
341 presented in Table 1 by the model (5) and (6) for the
342 convex slopes is ± 0.04 or $\pm 3.8\%$ of the average
343 wetness coefficient K_W value.

344 4. GIS realization of the model

345 From the dependencies (1), (3)–(6) it follows that
346 a set of initial data that one needs for solving the task
347 of spatial distribution of soil moisture content
348 modelling on a slope or in a small catchment is
349 limited to the information contained in a digital
350 elevation model (DEM) of the territory. Based on GIS
351 technology maps of the spatial distribution of all
352 parameters of the model, such as relief form, aspect,
353 slope, slope profile shape, slope length and distance
354 from the divide can be generated.

355 We used the PCRaster GIS package (PCRaster
356 manual, 1998; Burrough and McDonnell, 1998) to
357 perform the following operations:

- 358 • construction of a local drainage direction map
359 using the *lddcreate* operator;

- 385 • construction of an upstream elements map, every
- 386 cell of which contains the upslope contributing
- 387 area using the *accuflux* operator;
- 388 • construction of a hydrographic network map as
- 389 the sequence of cells with watershed area
- 390 exceeding some threshold value (40,000–
- 391 60,000 m² for the conditions of the studied
- 392 area), using the *if* operator;
- 393 • construction of a map of aspect using the *aspect*
- 394 operator;
- 395 • construction of the relative length of slopes
- 396 (l/l_{\max}) map using the *spread* and *spreadzone*
- 397 operators;
- 398 • construction of longitudinal curvature of slopes
- 399 map using the *profcurv* operator and the
- 400 selection of sites with (a) convex and (b)
- 401 straight or concave slope shapes using the
- 402 *windowaverage* and *if* operators,
- 403 • construction of the wetness coefficient K_W map
- 404 using the *if* operator and
- 405 • construction of a soil moisture content map in
- 406 absolute values (mm or %) by multiplying

the K_W coefficient map and measured values of 433
soil moisture content of the upper soil layer at 434
the meteorological station or stations situated in 435
the given domain (on a ‘flat surface’). 436

5. Model testing and discussion 437

The model was tested using soil moisture measure- 441
ments made by the staff of Boguslav Field Exper- 442
imental Hydrological Base, Kiev region of 443
Ukraine (Fig. 1) during 1981–1987 in the small 444
experimental catchments Ploskiy with the drainage 445
area of 0.08 km², Pridorozniy with the drainage 446
area of 0.42 km² and Lesnichiy with the drainage 447
area of 0.20 km². The Ploskiy and Pridorozniy 448
catchments are sloping watersheds without expressed 449
thalwegs and in general have northern aspects ranging in 450
some sites from north-western to north-eastern. The average 451
surface slope of these catchments are 2.47 and 2.27%, 452
respectively (Materials, 1980–1989). The Lesnichiy 453
catchment is characterized by a dense and deep 454
watershed network. 455

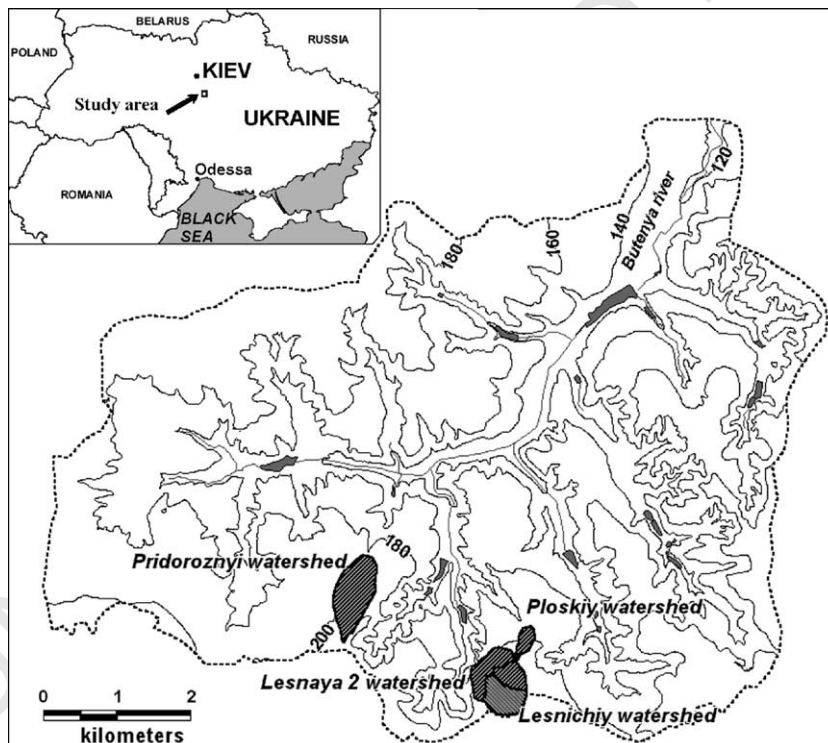


Fig. 1. Location of the study area. 456
457
458
459
460
461
462
463
464
465
466
467
468
469
470
471
472
473
474
475
476
477
478
479

481 drainage net and much greater slope angles and
 482 considerably greater aspect range which is larger than
 483 in the first two catchments. The average slope of this
 484 catchment is equal to 16.9%, the maximum slope is
 485 more than 50%. North-Eastern, North-Western,
 486 South-Western and South-Eastern aspects prevail.

487 DEMs of the experimental catchments used for
 488 computer simulation are created with the help of
 489 large-scale topographical maps with the spacing of
 490 contourlines ranging from 0.2 (for the Ploskiy
 491 catchment) to 1.0 m (for the Lesnichiy and Pridorozniy
 492 catchments). For the generation of the DEMs
 493 we used elevations of topographical surface for the
 494 Ploskiy catchment in 3108 points, for the Lesnichiy
 495 catchment—approximately in 7000 points and for the
 496 Pridorozniy catchment—in 506 points. The DEM for
 497 the Lesnichiy catchment was constructed as a part of
 498 DEM for the Lesnaya-2 catchment (see Fig. 1). The
 499 Lesnaya-2 catchment has the soil, geomorphological
 500 and vegetative conditions identical with the Lesnichiy
 501 catchment, but the drainage area is approximately
 502 three times larger (0.57 km²). Because of this, it was
 503 used for numerous experiments on modelling the
 504 spatial distribution of soil moisture content. For
 505 generating the DEM of the Lesnaya-2 catchment we
 506 used spot elevations at 20,634 points. The spatial
 507 interpolation of points values was done by *ordinary*
 508 *kriging procedure* (Burrough and McDonnel, 1998)
 509 using a package of geostatistical analysis and model-
 510 ling (Gstat, Pebesma and Wesseling, 1998). The
 511 accuracy of the DEMs was estimated by comparison
 512 of heights of the topographical surfaces derived from
 513 the topographical maps at digitizing points, and the
 514 calculated values of the appropriate cells of the DEMs.
 515 Standard deviations of the errors for the Ploskiy
 516 catchment are 0.012 m, for the Lesnaya-2 catchment,
 517 0.103 m, and for the Pridorozniy catchment, 0.116 m.
 518 The size of a raster cell of the DEMs are 5 × 5 m for
 519 the Ploskiy and the Pridorozniy catchments and
 520 4 × 4 m for the Lesnaya-2 and the Lesnichiy catch-
 521 ments (Fig. 2).

522 The soil cover of the experimental catchments is
 523 leached chernozem (in the Pridorozniy catchment),
 524 podzolised dark-grey forest (in the Ploskiy catchment)
 525 and podzolised grey forest (in the Lesnichiy catch-
 526 ment), eroded to varying degrees on loess with silt-
 527 loamy texture. The depth to the groundwater table in
 528 the investigated catchments during the summer season

529 is 20–25 m on divides and 10–15 m in the gullies.
 530 The catchments are covered by a single type of
 531 vegetation and that is why the soil moisture
 532 distribution is caused by relief only. The soils of the
 533 Ploskiy and Pridorozniy catchments are ploughed and
 534 used for agricultural crop cultivation (winter wheat,
 535 corn, sugar beet and others) in crop rotations. These
 536 catchments from top to bottom are within one crop
 537 rotation field. The Lesnichiy catchment is completely
 538 covered by planted deciduous forest of about a
 539 hundred years age weighting.

540 The soil sampling for moisture content determi-
 541 nation in the Ploskiy catchment area was done at 10
 542 points, in the Pridorozniy catchment, at 8 points and in
 543 the Lesnichiy catchment, at 20 points more or less
 544 equally distributed within the catchments areas. The
 545 soil moisture content was determined by the thermo-
 546 static-weighting method. The soil samplings were
 547 done twice a season up to the depth of 1 m; in the
 548 upper 10 cm layer at 5 cm intervals and in the lower
 549 layers, at 10 cm intervals in four replics at each point.

550 Based on these data, long term seasonal average
 551 values of the moisture content in the upper 50 cm soil
 552 layer were calculated for each point. Then the
 553 corresponding wetness coefficient (K_w) values were
 554 calculated which were used in the further analysis. As
 555 the soil moisture content on a 'flat surface' for the
 556 Ploskiy and Pridorozniy catchments we used the soil
 557 moisture content at the points situated near the divides
 558 with very small surface slopes (one point for every
 559 catchments). In the Lesnichiy catchment we used the
 560 average soil moisture content value for 5 points
 561 situated either on the divide or nearby it. The analysis
 562 of the results showed that the K_w values determined
 563 from seven years of observations for each catchment
 564 correlate well with the amplitude of surface aspect
 565 variations of the catchments. This is not surprising
 566 because the surface aspect is one of the main factors
 567 determining the spatial distribution of soil moisture
 568 content. The surface aspects of the Ploskiy and
 569 Pridorozniy catchments are similar (Northern) and
 570 the wetness coefficients range from 0.90 to 1.07
 571 (spatial coefficient of variation C_v of the K_w is 3.2 and
 572 3.7%, respectively). The surface of the Lesnichiy
 573 catchment has slopes with both northern and southern
 574 aspects. Because of this the K_w coefficient ranges here
 575 from 0.84 to 1.24 and spatial coefficient of variation
 576 C_v is 12.6%.

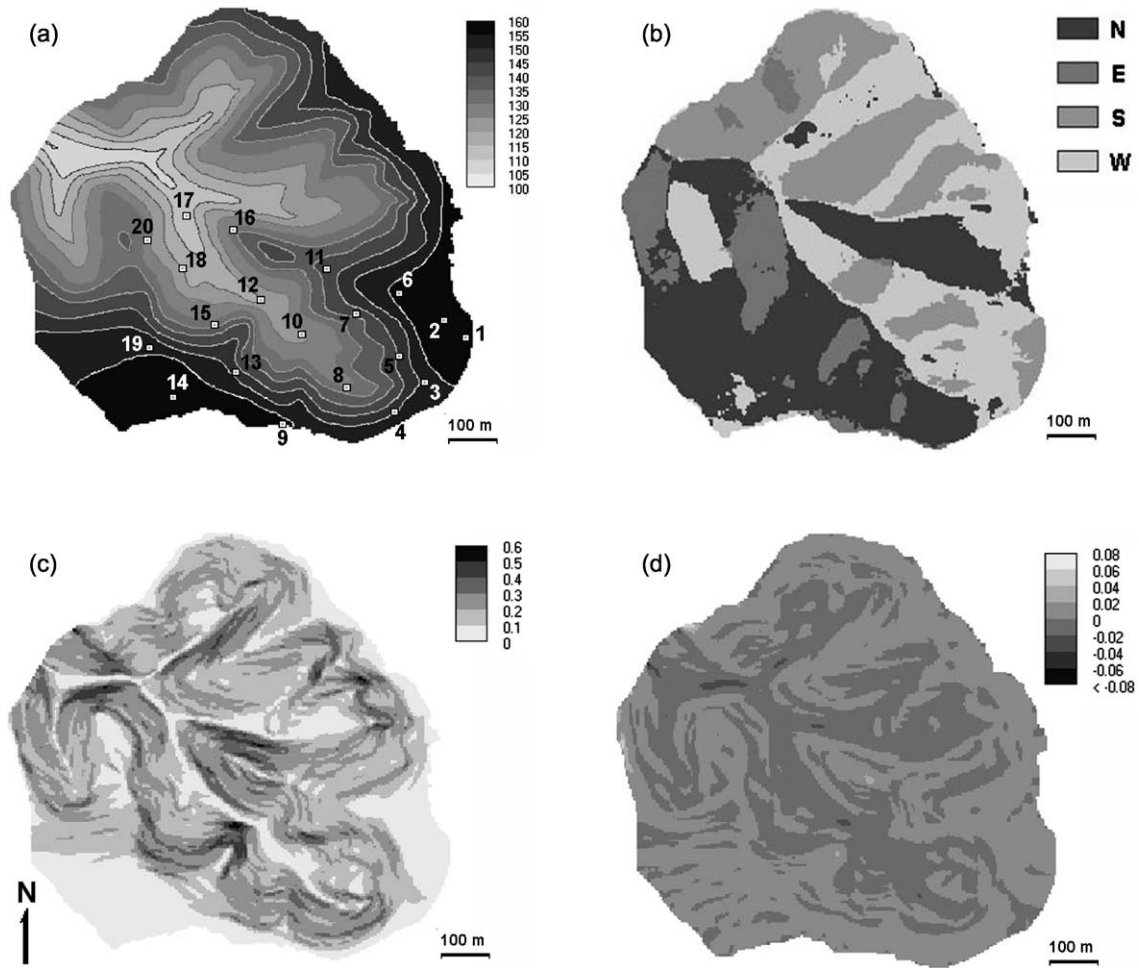


Fig. 2. DEM with contour lines and measurement points (a), aspect (b), gradient (c) and longitudinal profile curvature (d) maps for the Lesnaya-2 catchment.

The results of the model application to the given catchments showed that for all of them Eqs. (1), (3)–(6) for the moisture content in the upper 50 cm soil layer fit the field data. Fig. 3 shows values of the wetness coefficient K_W for the experimental catchments Ploskiy, Pridoroznyi and Lesnichiy.

Root-mean-square error of estimated θ_w values for all 38 points of soil moisture content is ± 0.073 or 7.2% of the average value of the wetness coefficient (which equals 1.02). The distribution of errors is the following: in 21 points (55.3% of total quantity) the errors do not exceed $\pm 5\%$; in 32 points (84.2%) the errors do not exceed 10% and in 37 points (97.4%)

the errors do not exceed 15%. The greatest difference between the computed K_W values and the measured ones is 20.2%. The ratio of the root-mean-square error of the estimation (S) and the standard deviation of the K_W values (σ) for the considered data set equals 0.70. The ratio is used as a quality criterion of forecasting techniques in the practice of hydrological forecasts (Befany and Kalynin, 1983). It allows to evaluate the accuracy of the model as satisfactory ($0.50 < S/\sigma \leq 0.80$).

In the produced map as well as in the evaluation of accuracy given above we accounted for changes of the profile shape along the slope length. An

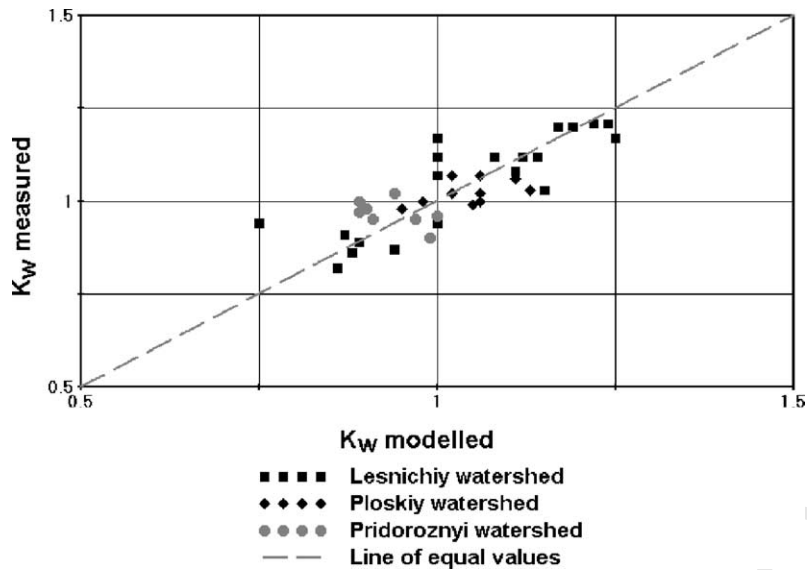
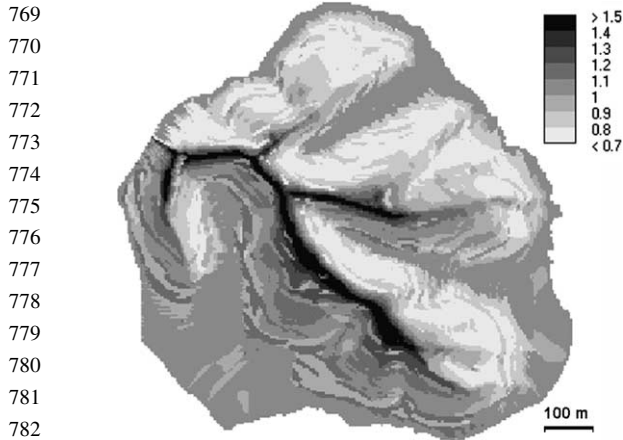


Fig. 3. Measured and simulated the wetness coefficient K_W values.

attempt to estimate the spatial soil moisture distribution on the whole slope using either Eqs. (1), (3) and (4) (i.e. considering the whole slope as straight or concave) or Eqs. (1), (5) and (6) (the whole slope is convex) led to a considerable decrease in accuracy. The reason is the fact, that as a rule, in nature there are no slopes with 'straight', 'concave' or 'convex' profile shapes over the whole length of the slope. Even taking into account only the general shape of the slope profile (slope macro-shape) the most typical longitudinal shape of slopes, at least in the regions under consideration, is a complex one. As a rule, the slopes have a convex shape in the upper part and they have a concave shape in the lower part. Because of this one must use different expressions of the model: (3) and (4) or (5) and (6) for different parts of one and the same slope according to the character of its curvature. Besides, smaller scale variations of the slope profile with a period from a few to tens and even hundreds of meters are often superimposed on a slope macro-shape (Svetlitchnyi, 1991, 1995). This causes a repeated change of the character of curvature of a slope profile over its length. For this reason, a model of soil moisture spatial distribution must have the ability to consider all these fundamental features of slope morphometry.

In the model developed here the longitudinal slope profile shape is accounted for by the PCRaster package *profcurv* operator, which can calculate curvature of the slope surface and its sign for each raster cell. With the use of the conditional operator *if* and a threshold curvature value, the magnitude of which was determined empirically in accordance with cell size, each cell is classified into a slope profile type: (a) straight or concave; (b) convex.

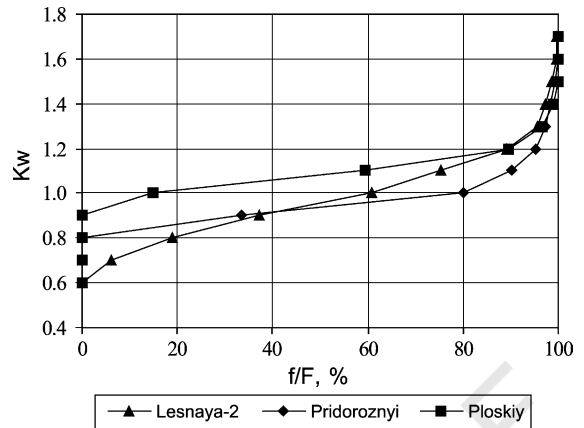
Fig. 4 shows the computed map of the spatial distribution of the wetness coefficient K_W the Lesnaya-2 catchment with the drainage area of 0.57 km², which includes the Lesnichiy catchment as a part. It is obvious that the spatial distribution of soil moisture content within this rather small experimental catchment area is characterized by a significant difference. The peculiarities of this difference within the catchments Ploskiy and Pridoroznyi on one hand, and Lesnaya-2 on the other hand, are rather significant. Even without taking into account areas with extreme values of the wetness coefficient which occupy less than 5% of catchments area, the K_W values for the Ploskiy and the Pridoroznyi catchments range from 0.8–0.9 to 1.2–1.3. The part of the catchment area with K_W values of 1.0 ± 0.10 makes up 60%, and the part of the catchment area with K_W values of 1.0 ± 0.20 makes up 90–95% of the total catchment area. In



783 Fig. 4. Simulated map of spatial soil moisture distribution (in terms
784 of values of the K_W coefficient) in the Lesnaya-2 catchment for the
785 summer season.

786
787
788 the Lesnaya-2 catchment the range of K_W values
789 (disregarding the extreme values within the area of
790 distribution less 5%) is much greater and equals
791 0.61–1.30. The part of the Lesnaya-2 catchment
792 with K_W values of 1.0 ± 0.10 makes up only 38%
793 of all the area. At the same time, the part of the
794 Lesnaya-2 catchment with the K_W values of
795 1.0 ± 0.20 makes up about 70%. In 19% of the
796 catchment area the K_W coefficient is 0.6–0.8 and in
797 about 10% of the catchment area it is 1.2–1.7.

798 The geostatistical analysis of the estimated
799 spatial pattern of the soil moisture in the exper-
800 imental catchments Pridoroznyi and Lesnaya-2
801 carried out using the Gstat package confirms the
802 results of researches of spatial structure of the soil
803 moisture distribution during the dry summer period
804 by Western et al. (1998). The researches were
805 executed on the basis of detailed field measure-
806 ments (at 500–2000 points) of spatial soil moisture
807 pattern in the 10.5 ha Tarrawarra catchment in
808 temperate south-eastern Australia. Exponential vari-
809 ogram models fit the sample variograms closely
810 and correlation lengths are 50–60 m both for the
811 Tarrawarra catchment, and for the Pridoroznyi and
812 Lesnaya-2 catchments. But for the Ploskiy catch-
813 ment spatial structure of the estimated soil moisture
814 distribution has other character. The experimental
815 variogram has no the expressed sill and it is in
816 the best way described by gaussian model. From



831 Fig. 5. Spatial soil moisture distribution curves for the experimental
832 catchments.

833
834 here the conclusion that the spatial structure of soil
835 moisture distribution on slopes and in small
836 catchments may be various. This conclusion proves
837 to be true by the curves of spatial soil moisture
838 distribution in the experimental catchments (Fig. 5)
839 constructed on the basis of the estimated spatial
840 soil moisture patterns. They can be represented by
841 a double parabolic curve. The similar conclusion
842 concerning the form of the curve of spatial
843 distribution of soil moisture capacity over the
844 catchment is received by Jayawardena and Zhou
845 (2000) on the basis of numerical experiments with
846 the runoff generation model. However, parameters
847 of these curves as it is follows from Fig. 5 vary
848 depending on spatial distribution of aspects,
849 gradients, profile and plan slope curvatures in the
850 catchments.

851 The statistical parameter values of the estimated
852 distribution of the wetness coefficient K_W within
853

854
855 Table 2

856 Statistical parameters of simulated spatial distribution of the
857 wetness coefficient K_W for the experimental catchments (dimen-
858 sionless)

Catchment	Drainage area, km ²	Average value	Standard deviation	Coefficient of variation
Ploskiy	0.08	1.09	0.098	0.090
Pridoroznyi	0.42	0.96	0.117	0.122
Lesnaya-2	0.57	0.97	0.187	0.193

865 the experimental Ploskiy, Pridorozniy and Lesnaya-
866 2 catchments are given in Table 2.

867

868

869 6. Conclusions

870

871 The analysis of the spatial distribution of soil
872 moisture showed significant variability even within
873 small plane catchments. The coefficient of variation
874 C_v of soil moisture for the experimental catchments
875 examined here is 0.09–0.19. There is only 40–60%
876 of the area within the limits of a 10% deviation
877 from the content of a soil moisture measured on a
878 flat surface. In the remaining part of the
879 catchment areas, the moisture content in the topsoil
880 layer ranges over wide limits. In the upper part
881 of straight and concave slopes and in the lower part
882 of convex slopes of south and south-west
883 aspects the relative wetness coefficient is 0.6–
884 0.7, on the foot of slopes of north and east
885 aspects, regardless of their profile shape, it reaches
886 1.5–1.6.

887 Spatial distribution of soil moisture over catch-
888 ments can be described by a double parabolic curves.
889 But parameters of these curves significantly vary
890 depending on slope morphometry of the catchments—
891 first of all on spatial distribution of aspects, gradients,
892 profile and plan slope curvatures.

893 The researches presented here showed that
894 the estimation of the soil moisture spatial distri-
895 bution as a function of terrain characteristics
896 using opportunities of the GIS technology is
897 promising.

898

899

900 Acknowledgements

901

902 This research is a part of the scientific research
903 project IC15-CT98-0215 ‘SPARTACUS’, financed
904 by European Community in the framework of INCO-
905 COPERNICUS Program.

906

907

908 References

909

910 Befany, N.F., Kalynin, G.P., 1983. Exercises and Methodical
911 Developments on Hydrological Forecasts, Hydrometeoizdat,
912 Leningrad, pp. 391 (in Russian).

- Burrough, P.A., McDonnel, R.A., 1998. Principles of Geographical Information Systems for Land Resources Assessment, Oxford University Press, Oxford, pp. 333. 913
914
Burt, T.P., Butcher, D.P., 1985. Topographic controls of soil moisture distribution. *Journal of Soil Science* 36, 469–486. 915
916
Fedoseev, A.P., 1959. Soil moisture in connection with relief of terrain. *Transactions of KazNIGMI* 13, 66–88.(in Russian). 917
918
Fishman, M.I., 1968. Accumulation of water in soils of different forest-steppe complexes as factor of their ?groeconomic grouping. *Pochvovedenie* 1, 51–65.(in Russian). 919
920
Fitzjohn, C., Ternan, J.L., Williams, A.G., 1998. Soil moisture variability in semi-arid gully catchment implication for runoff and erosion control. *CATENA* 32 (1), 55–70. 921
922
Florinsky, I.V., Eilers, R.G., Manning, G.R., Fuller, L.G., 2002. Prediction of soil properties by digital terrain modelling. *Environmental Modelling and Software* 17 (3), 295–311. 923
924
925
926
Furley, P.A., 1971. Relationships between slope form and soil properties developed over chalk parent materials, Slopes, Forms and Process. Institute of British Geographical Special Publication, vol. 3, pp. 141–164. 927
928
929
930
Gerrard, A.J., 1981. Soils and Landforms: An Integration of Geomorphology and Pedology, George Allen & Unwin, London, pp. 219. 931
932
Golubeva, T.A., 1967. The complex characteristic of a radiative regime of slopes. In: Goltsberg, I.A., (Ed.), *Microclimate of the USSR*, Hydrometeoizdat, Leningrad, pp. 11–37, (in Russian). 933
934
935
936
Hawley, M.E., Jackson, T.J., McCuen, R.H., 1983. Surface soil moisture variation on small agricultural watersheds. *Journal of Hydrology* 62, 179–200. 937
938
Izmailsky, L.A., 1894. Soil Moisture Content and Ground Water in Connection with the Relief of Terrain and Cultural Condition of Soil Surface, Poltava, pp. 24 (in Russian). 939
940
Jayawardena, A.W., Zhou, M.C., 2000. A modified spatial soil moisture capacity distribution curve for Xinanjiang model. *Journal of Hydrology* 227, 93–113. 941
942
943
Kondratjev, K.J., Monolova, M.P., 1961. Radiative Balance of Inclined Surfaces, Proceeding of II All-Union Conference on a Light Climate, Moscow, Rosstrojizdat, pp. 45–60 (in Russian). 944
945
946
Korn, G.A., Korn, T.M., 1968. *Mathematical Handbook for Scientists and Engineers. Definitions, Theorems, and Formulas for Reference and Review*, McGraw-Hill, New York, 2nd enl. and rev. ed., pp. 1130. 947
948
949
950
Materials of Observations of the Boguslav Field Experimental Hydrological Base, 1980–1987. Kiev-Obninsk, 1984–1989, pp. 15–22 (in Russian). 951
952
953
Mazur, L.P., 1975. Analysis and calculation of moisture content in soils of mountain declivities in Zailiysky Alatau. *Geographical collection of Kazakh University* 2, 137–141.(in Russian). 954
955
956
Naden, P.S., Blyth, E.M., Proadhurst, A.D., Wright, I.R., 2000. Modelling the spatial variation in soil moisture at the landscape scale: an application to five areas of ecological interest in the UK. *Hydrological Processes* 14 (4), 785–809. 957
958
959
960

961	PCRaster manual, 1998. Version 2. Faculty of Geographical	Shpak, I.S., 1964. Methods of calculation of soil water content of	1009
962	Sciences Utrecht University and PCRaster Environmental	upper 10-cm soil layer. Proceedings of UkrNIHMI 46,	1010
963	Software, Utrecht, The Netherlands, pp. 368.	91–110.(in Russian).	1011
964	Pebesma, E.J., Wesseling, C.G., 1998. Gstat: a program for	Shvebs, A.V., 1968. Distribution of soil moisture content within	1012
965	geostatistical modelling, prediction and simulation. Computers	slopes depending on relief and past soil erosion of soils.	1013
966	and Geosciences 24 (1), 17–31.	Meteorology, Climatology and Hydrology 3, 172–178.(in	1014
967	Romanova, E.N., 1966. Redistribution of the moisture on gentle	Russian).	1015
968	slopes and at them foots in a warm season. In: Goltsberg, I.A.,	Silvestrov, S.I., 1955. Relief and Agriculture, ?oscow, Selkhozizdat,	1016
969	(Ed.), Microclimatology, Hydrometeoizdat, Leningrad, pp.	pp. 288 (in Russian).	1017
970	3–18, (in Russian).	Svetlitchnyi, A.A., 1991. Relief conditions of slope erosion process	1018
971	Romanova, E.N., 1971. Approach of measurement and mapping of	and questions of its modelling. Geography and Natural	1019
972	soil moisture using morphometric data. In: Goltsberg, I.A.,	Resources 4, 123–131.(in Russian).	1020
973	Davitaya, F.F. (Eds.), Climate of Soil, Hydrometeoizdat,	Svetlitchnyi, A.A., 1995. Quantitative assessment of slope	1021
974	Leningrad, pp. 39–51, (in Russian).	erosion process and optimization of soil erosion hazard	1022
975	Romanova, E.N., 1977. Microclimatic Variability of Main Elements	lands usage. Dr (Geogr.) Sc. Theses, Odessa, Odessa State	1023
976	of Climate, Hydrometeoizdat, Leningrad, pp. 288 (in Russian).	I.I. Mechnicov University, pp. 47 (in Ukrainian).	1024
977	Shipulin, V.F., 1973. Distribution of water content of slope soils.	Western, A.W., Blöschl, G., Grayson, R.B., 1998. Geostatistical	1025
978	Problems of Geography of (Soviet) Far East, Collection 13,	characterisation of soil moisture patterns in the Tarrawarra	1026
979	147–150.(in Russian).	catchment. Journal of Hydrology 205 (1/2), 20–37.	1027
980			1028
981			1029
982			1030
983			1031
984			1032
985			1033
986			1034
987			1035
988			1036
989			1037
990			1038
991			1039
992			1040
993			1041
994			1042
995			1043
996			1044
997			1045
998			1046
999			1047
1000			1048
1001			1049
1002			1050
1003			1051
1004			1052
1005			1053
1006			1054
1007			1055
1008			1056