ID: 44

The Experience of the Efficient Planning of RWS network in Moscow Region

Natalia A. Bezrukova, Evgeny A. Stulov and Alexander Ya. Naumov

Central Aerological Observatory, Moscow Region
Email: nataly_bez@yahoo.com, stulov_e@yahoo.com, aynaumov@mail.ru

ABSTRACT

The climate of Moscow Region is highly variable, winter precipitation in particular. Snowfalls present the greatest difficulty in winter motor road maintenance. With Moscow Region divided into 6 areas, climatic estimates have been obtained for each of them with a view to winter road maintenance problem. The areas were distinguished by relief parameters, using a specially evaluated averaged relief matrix. The coefficient of correlation "relief vs. precipitation" was estimated by calculating a sample linear coefficient of the correlation between similar elements of the matrices of relief and precipitation fields. For planning an RWS network efficiently, it is required that measurement data from a single site inside a specific area be sufficiently representative of the whole area. A root-mean-square error is taken as error criterion. The number of network sites in a separate area depends on the space-and-time precipitation parameter variability and the given interpolation error. The density of an RWS network for the areas of Moscow Region has been estimated, using a correlation analysis for solid and mixed precipitation fields. An RWS arrangement pattern for Moscow Region has been proposed.

Keywords: density of RWS network, coefficient of correlation, network sites

1. INTRODUCTION

Creating a special weather forecast system for motor roads is associated with large expenses. Therefore, optimization of this system, including the rational planning on the network and deployment of road weather stations (RWS) is becoming topical. This paper presents grounds for the rational planning of Moscow Region RWS network. The authors use the technique of estimating weather stations optimal density, described in theoretical papers on statistical meteorology [3], [6-9], for Moscow Region physiographic conditions.

2. STATE-OF-THE-ART

2.1 Management agents, methods of meteorological assurance, and weather stations network

All the activity devoted to weather observations and forecasting builds upon routine, timed measurements of weather parameters by direct in situ techniques on the ground and upper-air sounding networks as well as by indirect remote radar and satellite-borne techniques. The main coordinator in weather observations and forecasting for various users is the Federal Service for Hydrometeorology and Environmental Monitoring of Russia (Roshydromet). With the development of the RWS network, the Federal Motor Road Service may also become an agent of specialized meteorological assurance management.

Nowadays, Moscow Region observational network comprises 15 hydrometeorological network stations and 2 posts as well as 4 airport stations at Sheremetyevo, Bykovo, Vnukovo, and Domodedovo. Over the whole territory the stations make simultaneous observations at 0:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00 Moscow winter time.

2.2 Network planning for specialized meteorological assurance

Apart from general meteorological information, the road maintenance service requires specialized data on glaze, heavy precipitation with intensity I>0.5 mm/h, snowfalls with intensity I> 0.3 mm/h, snow cover height in access of 20-25 cm per 12 h, snow banks, wind speed over 10-15 m/s, squalls with speeds over 25 m/s, visibility range of less than 500 m in the daytime and less than 1 km at nighttime.

The deployment of network stations is part of a major problem of creating an optimal system of meteorological observations which, apart from spatial arrangement pattern, also concerns the other observational system parameters, i.e. a set of elements to be measured, measurement accuracy and frequency. The system under consideration is to permit obtaining the values of meteorological elements with a given accuracy for all the sections of the existing motor road network rather than only at weather station locations. The requirements for the rational planning of a motor road network must be formulated based on calculations of the necessary and sufficient network density ensuring a given measurement error.

3. MOSCOW REGION RELIEF, CLIMATE AND MOTOR ROAD NETWORK

3.1 Relief

Moscow Region relief is hilly (Fig.3.1) and typical of the Russian Plain. It is most clearly seen in its Klin-Dmitrov Ridge (200-300 m) extending from northeast to southwest. In the south, it gradually transforms to the rolling Moscow River - Oka Plain (150-180 m) and slightly billowy watersheds of the river valleys. The southeast of the region is occupied by part of Meshchora Lowland with hills (120-150 m) and is largely waterlogged. The south of Moscow Region is occupied by the northern part of the Central Russian Hills (150-200 m) indented by river valleys.

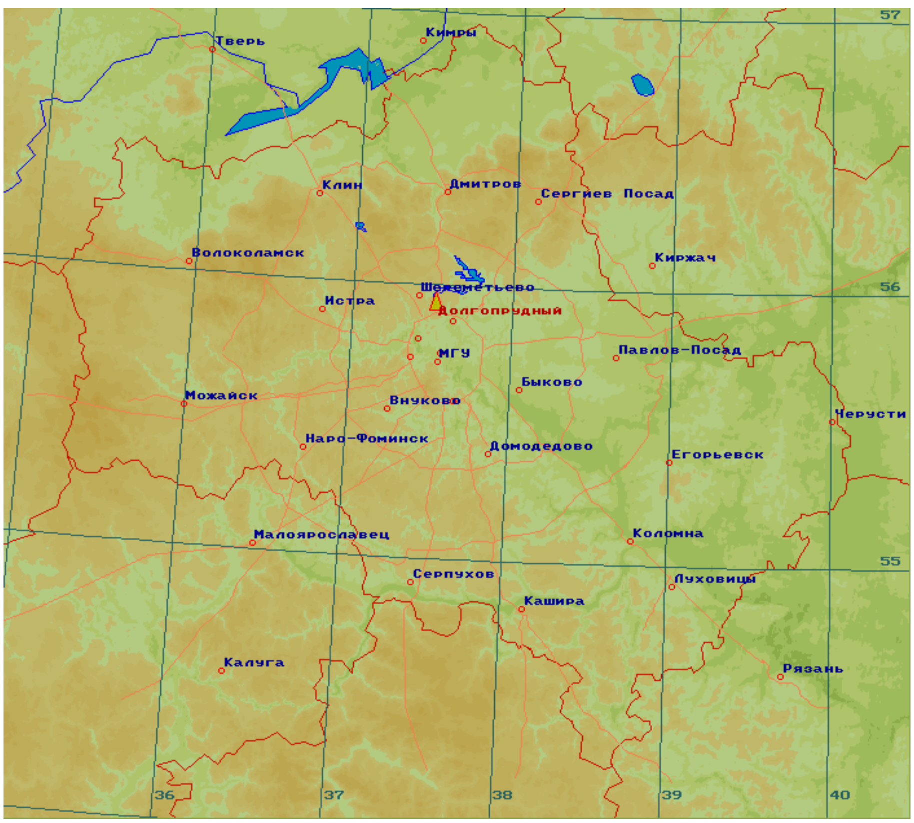

Fig. 3.1. Moscow Region relief

3.2 Climate and climatic zones

Moscow Region temperate continental climate with its unstable atmospheric circulation dominated by westerly transport is characterized by high weather parameter variability throughout the cold half of the year. The annual mean precipitation amount is 600-700 mm. The winter is mild, with frequent thaws, and snowy. The average snow cover thickness is 30-40 cm, with a maximum of 70 cm and minimum of 10-15 cm. Fog frequency in winter is 2 –4 days per month, being the highest in the vicinity of Moscow due to the dusty environment, and in the southeast, over Meshchora lowlands. The winds are predominantly westerly, 3-4 m/s. Snowstorms occur 6-8 times per month. The climate of the cold seasons is highly variable. Frequent thaws and heavy snowstorms complicate motor road maintenance in winter.

In any region there are zones with similar climatic conditions which are due to the specific height of given localities, their orientation with respect to the prevailing air mass transport, their position relative to the nearby city or river valley, and are characterized by relative stability of climatic characteristics. In Moscow Region, the following climatic zones can be distinguished (Fig.3.2) based on the relief parameters such as height difference (roughness) and mean height. For this purpose, a specially computed averaged relief matrix was employed.

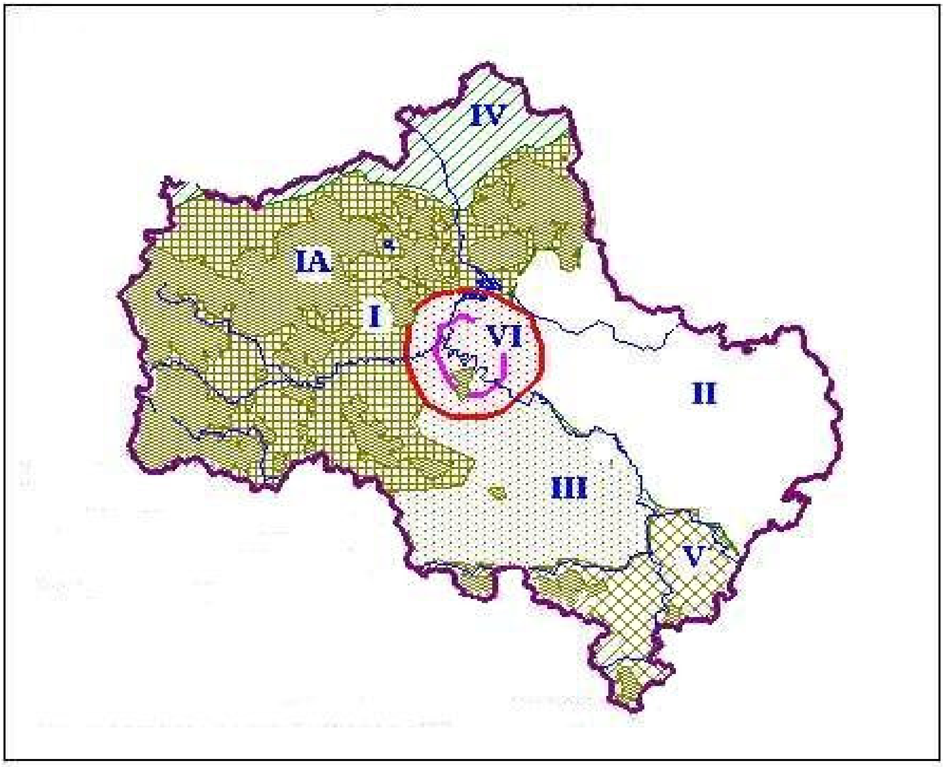

Fig.3.2. Moscow Region climatic zones

(Zone I – Moscow Hills, 200-250 m, relative height difference 100-150 m; Ia – Klin-Dmitrov Ridge, 200-300 m, relative height difference 100180 m; Zone II – Meshchora Lowland 110-160 m, relative height difference 30-50 m; Zone III – Moscow River-Oka Plain 150-200 m, relative height difference 40-50 ; Zone IV – Higher Volga Lowland, 100-150 m, relative height difference 40-50 m; Zone V – the right bank of Oka on the Central Russia Plain, 150 m; Zone VI – the zone of Moscow industrial influence (10-15 km from the border of Moscow).

Relief is what governs the formation of a nonuniform weather parameter field. Zones with a high probability of glaze formation (Ia) require a denser RWS network. On plains, the network density may be lower.

3.3 Road network

Moscow Region (50,000 km2) has a dense network of motor roads. The Federal road network arrangement follows a radial-ring pattern, which inherently entails irregular density. The territorial road network is irregular both in its density and traffic intensity (Table 3.1).

3.4 The influence of Moscow Region relief on precipitation

Precipitation is one of the parameters critical for winter motor road maintenance [1], [2], [11]. Based on the precipitation radar measurements provided by the CAO Radar Weather System [3] during a 7-year period, one of the co-authors [13], [14] has obtained the correlation between precipitation distribution and relief for Moscow Region. The correlation coefficient 'relief-precipitation', **r**, was determined by calculating the sample linear coefficient of the correlation between analogous elements of the matrices of relief and precipitation fields.

Climatic Zones	Square, km^2	Local Roads, km		Federal Roads, km		H average m	Mean square deviation
		Length , km	Density, 1/m	Length, km	Density, 1/m		
I	**18800 (40%)**	**4744.8**	**0.26**	**845.0**	**0.045**	**200**	**30**
II	**10500 (22%)**	**2747.7**	**0.25**	**194.0**	**0.018**	**135**	**15**
III	**7000 (15%)**	**2074.0**	**0.30**	**512.0**	**0.073**	**170**	**20**
IV	**3500 (8%)**	**1193.9**	**0.34**	**102.0**	**0.029**	**140**	**20**
V	**3900 (10%)**	**1169.3**	**0.29**	**133.0**	**0.034**	**160**	**21**
VI	**2300 (5%)**	**566.5**	**0.25**	**228.1**	**0.099**	**170**	**25**

Table.3. 1. Motor roads length (14510,3 km total) and density with zonal relief features

Precipitation amount in the area decreases in the direction from W-N-W to E-S-E, which, on the whole, coincides with the direction of the terrain height gradient. Precipitation amount is the largest at the upwind slopes of the Klin-Dmitrov Ridge and over the territory of Moscow. The annual precipitation increase over the Klin-Dmitrov Ridge makes up 10-15% of the mean precipitation amount over the area, or 80-100 mm per 100 m height. The precipitation minimum due to the urban influence is shifted eastward.

In some cases, with a positive 'relief-precipitation' correlation, precipitation amount increases by 30-60% per 100 m height. In terms of absolute values, precipitation increase grows with precipitation layer increasing per rain. For a fixed profile of relief with a height difference of 100-150 m per 20 km and air flow speed of 15-25 m/s, precipitation amount may increase from the bottom to the top of the ridge by hundreds percent. The formation of glaze on the roads is also dependant on the roughness of relief.

4. EFFICIENT NETWORK PLANNING

An efficiently planned network should meet the requirement of measurement data representativeness. This requirement implies that measurements at a certain point are to represent with sufficient accuracy the parameter values measured over the surrounding territory. The parameter values obtained for any other point of the territory are to be within given accuracy limits. The quantitative characteristic of representativeness is obtained by the method used for extending pointwise data onto the surrounding territory.

The problem of efficient RWS network arrangement is part of a major problem of creating an optimal observational system. The latter is to provide for all parameters intrinsic to observational systems: a set of RWS parameters to be measured, measurement accuracy, measurement frequency, and spatial density. Once, given all the rest of RWS system parameters, you only need to determine measurement site locations, you are confronted with the problem of efficient network arrangement.

4.1. Stating the problem of measurement network planning

The technique of efficient RWS arrangement is described in [7-9]. Precise values of measured parameters are only known for the locations of the measurement stations, with instrumental error assumed to have been specified. At the other points of the territory concerned the parameter values are obtained by interpolation. Hence the main requirement: a network of measurement stations is to enable the determination, with acceptable accuracy, of weather parameter values at each point over the territory rather than only at station locations. Therefore, an error of interpolating a parameter value to any point of the territory is not to be too large. The criterion is a root-mean-square interpolation error. The currently available techniques of measurement network planning allow one to determine the number of measurement points over a given territory that would provide the given accuracy of the mean parameter value for a particular area (s). This depends on space and time parameter variability and pre-specified interpolation error, weather parameter variability intrinsic to a particular territory playing the key role. The variability can be determined through correlation analysis, by applying this estimation procedure to precipitation fields measured at the stations of Moscow Region's basic observational network.

4.2. Evaluation procedure

Due to the high natural variability of precipitation fields over short time spans such as 12 h or less, the relative error with which data from separate points characterize average precipitation layer over a particular area, rather than the interpolation accuracy, is used as a quantitative criterion of precipitation measurement representativeness. This very approach was proposed by R.L. Kagan in [10], developed L.S.Gandin and R.L. Kagan in [5], and is widely applied not only to precipitation, but to other weather parameters as well. The relative root-mea-square error of evaluating precipitation layer is given by

$$Z(1,s) = \frac{E(1,s)}{\bar{R}}, \tag{1}$$

where R is the mean total precipitation amount, s is the area, E is the error with which the values from a single station characterize the mean over area s.

As the area inlarges, the error of precipitation layer estimation increases. Thus the representativeness of data from a single rain gage station diminishes. For precipitation amount per short period (half a day or less), the error in the mean value representation proves large with a dense observational network as well. Even in the case when only one rain gage is available for a 1 km^2 area, the root-mean-square errors per half a day exceed 20-30% of the average value. So precipitation amount measurements per 12 or 24 hours cannot be considered representative even for small areas. Hence the necessity of analyzing the field of an overall network of measurement stations. In other words, reliable enough estimates of total precipitation amount for short time spans can only be obtained by averaging over vast territories with a large number of measurement stations. As shown in [10], in the case when over an area, s, n stations are relatively evenly distributed, the accuracy with which the arithmetic mean of their data characterizes the average value for this area is given by the equation

$$Z(n,s) = \frac{Z(1,s)}{\sqrt{n}} \tag{2}$$

where $s = s / n$ is the area per station. Therefore, even for short time periods one can obtain reliable enough estimates of total precipitation amount by averaging over large territories. Let us calculate $Z\ (n,\ s)$ by the formula from [10]:

$$Z(n,s) = C_v \sqrt{\frac{\eta^2}{n} + 0.23 \frac{\sqrt{s}}{\ell_0 n^{1.5}}} \tag{3}$$

where $C_v = \sigma / R$ is the coefficient of the variation of total precipitation amounts, σ- is the dispersion, η is the parameter characterizing random error in weather element measurements, $l_\mathbf{o}$ is the correlation radius characterizing the range over which the function changes the most, generally decreasing by a factor of e (**r** = 0,37). To make calculation using the method from [10], one must know the correlation radius $l_\mathbf{o}$. This quantity reflects the physiographic and climatic conditions typical of each particular territory. Its value, along with the other statistical characteristics evaluated for Moscow Region, is given in the next section.

4.3. Spatial cross correlation of winter precipitation field in Moscow Region

The most important weather parameter to provide motor road maintenance in winter and transitional periods is precipitation amount, particularly at temperatures from -5 to +5^{o}C when its intensity is especially high. In view of the fact that this parameter is also characterized by high space and time variability, it is the data on precipitation that serve as a statistical basis for evaluating weather network density. Also important is the road surface temperature. However, for lack of these data, the network density evaluation does not seem possible.

To estimate precipitation variability, 12-h measurement data on total amounts of solid, liquid, and mixed precipitation from all the Roshydromet network stations of Moscow Region for the period 1984-1989 were used [13], [14]. On the whole, 70 cases with liquid and mixed precipitation and 70 ones with solid precipitation were treated through statistical correlation analysis. The analysis included the 18 stations such as follows: Klin, Dmitrov, Volokolamsk, Istra, Mozhaysk, Pavlov-Posad, Kashyra, Lenino-Dachnoye, Naro-Fominsk, Serpukhov, Nemchinovka, Cherusti, Balchug, Krylatskoye, TSHA, VDNX, MGU, and AMCG at Vnukovo airport. The use of this large number of stations permits ruling out the effect of insignificant features of separate stations.

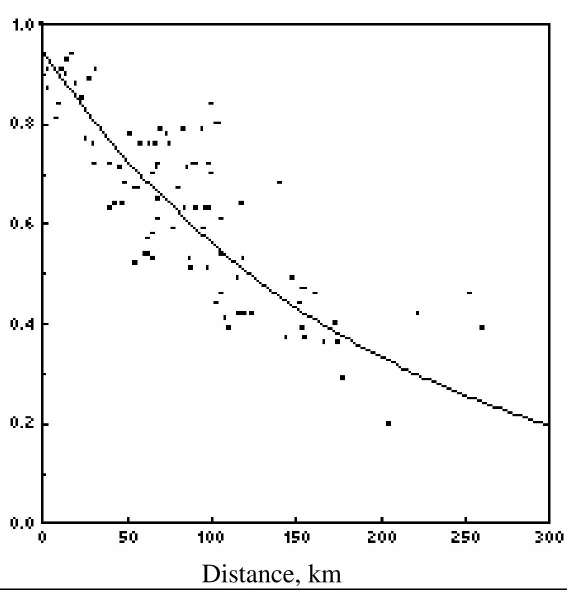

Fig. 4.1. Spatial correlation function for 12-h solid precipitation totals. Correlation coefficient **r** is plotted over Y-axis.

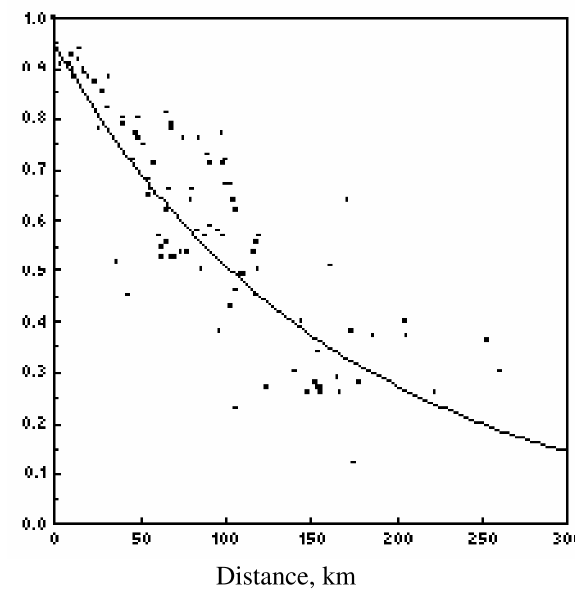

Fig. 4.2. Spatial correlation function for 12-h liquid and mixed precipitation totals. Correlation coefficient **r** is plotted over Y-axis.

To determine the correlation radius l_0 of precipitation fields for Moscow Region, the coefficients of paired cross correlation for 18 station of the region were calculated for liquid and mixed and, separately, for solid precipitation. Using these data, graphs were plotted showing paired correlation coefficients versus distance for liquid and mixed and solid precipitation, respectively (Figs. 4.1 and 4.2). The correlations obtained are well approximated by the correlation function. According to our calculations, the correlation radii for liquid and solid precipitation are 160 and 190 km, respectively. By formula (3) from [10] the mean relative error Z in estimating 12-h solid precipitation totals was calculated for different numbers of measurement stations.

According to Figs. 4.1 and 4.2, the correlation coefficient **r** for precipitation in Moscow Region rapidly decreases as the distance from the measurement station increases. Thus in winter, at distances of 25, 50, 100 km from the station, **r** decreases by 10-15%, 20-25%, and 40%, respectively. In summer, **r** decreases faster than in winter – by 30% and by over 50% at distances of 50 and 100 km, respectively. Isocorrelation fields for separate stations of the region (not shown here) are ellipse-shaped, with the longer axes oriented along the direction of prevailing air mass transport.

The root-mean-square value of the relative error $Z(n, s)$ (%) of estimating 12-h solid precipitation totals depending on the number of stations (n) and averaging area s (Table 4.1.). The correlation is such that pursuing error reduction leads to unreasonable increase of measurement network density. With the same number of network stations the error increases with s but insignificantly.

Number of stations	Averaging area s, km^2				
n	**2500**	**1600**	**900**	**400**	**100**
1	33	31	29	27	24
2	21	20	19	18	17
3	16	16	15	14	13
4	14	13	13	12	11
5	12	11	11	11	10

Table. 4.1. Mean relative error Z (%) in estimating 12-h solid precipitation totals over a given area depending on the number of measurement stations n.

For example, using one station per 900 or 2500 km^2 results in root-mean-square errors in determining 12-h precipitation totals of 29 and 33%, respectively, i.e., using nearly 3 times less stations leads to an error increase of only 4%.

4.4. Measurement network density estimates

Precipitation totals as the elements most important for winter motor road maintenance were used in our calculations. The obtained data describe spatial correlation as a function of the distance between the stations. The calculations were made specifically for Moscow Region. For other geographical areas, the dependence of the correlation function on distance will be different.

Area average S, km^2	Relative error, %			
	10	**20**	**30**	**40**
100	5	1	0	0
400	7	2	0	0
900	7	2	1	0
1600	9	2	1	0
2500	9	**2**	1	1

Table. 4.2. The number of stations per unit area providing a given relative error (%) in 12-h precipitation totals measured, depending on averaging area.

The calculation data permit the evaluation of the number of stations ensuring a given relative error (%) in measurements of 12-h precipitation totals, depending on an averaging area (Table 4.2). The analysis of the tabulated values shows that if a relative error of up to 30% is assumed to be acceptable, 1 observational station per 2500 km^2, i.e. around 20 stations for the whole of Moscow Region, is enough. A relative error of up to 20% is furnished with network density of 1 station per 100 km^2, which implies the necessity to have 400-450 observational stations within

Area average S, km^2		Relative error, %			
km^2	kmxkm	**10**	**20**	**30**	**40**
100	**(10X10)**	2350	470	0	0
400	**(20X20)**	819	234	0	0
900	**(30X30)**	364	104	52	0
1600	**(40X40)**	261	58	29	0
2500	**(50X50)**	171	**38**	19	19

Table. 4.3. The overall number of stations in Moscow Region providing a given relative error (%) in mean precipitation layer measurements for different averaging areas.

Moscow Region, or 2 stations per 2500 km^2, which would make up about 40 stations over the region. A 10% acceptable error demands a network enhanced to 5 stations per 100 km^2, or 9 ones per 2500 km^2. Therefore, to meet the most stringent requirements for accuracy, about 170 stations are necessary on the observational network of the territory concerned.

As per Sections 4.2 and 3.4, with the most acceptable error of 20%, the overall minimum number of stations for Moscow Region is 38, thus providing an average density of 2 stations per 50X50 km (Table 4.3). It should be emphasized that here the mean Moscow Region network density is meant, and in each particular climatic zone this parameter will differ from the mean value due to specific relief, climatic features, and road network density. Now that the total number of stations has been calculated for Moscow Region, let us discuss RWS network density for separately each climatic zone.

5. RWS NETWORK DENSITY IN DIFFERENT CLIMATIC ZONES OF MOSCOW REGION

In Section 4 it was determined that the minimum average density of RWS network for Moscow Region is 2 stations per 2500 km^2 , i.e. the initial minimum overall number of stations is 38. Considering the nonuniformity of the region's relief, combined with the climatic features and motor road network density (Table 3.3), the stations will be distributed unevenly, and the network densities for different climatic zones will differ (Table 5.1).

Climatic zones	Version I		Version II	
	Min. number	Density	Min. number	Density
I	18	2.39	20	2.66
II	5	1.19	6	1.43
III	5	1.78	5	1.78
IV	3	2.14	3	2.14
V	3	1.92	3	1.92
VI	4 (+6)	4.35 (10.9)	1 (+6)	1.08 (7.61)

Table. 5.1. Initially required RWS minimal number and network density in each climatic zone.

As 6 RWS's have already been installed on the Moscow Ring Motor Road, it will be possible to move some stations from zone VI (a circular zone with a 10-15 km radius of urban influence) to zones I (2 stations) and II (1 station). Due to this, the RWS network density will change (compare columns 3 and 5 of Table 5.1), in particular, increasing in zone I having the roughest relief up to 2.66 and zone II up to 1.43.

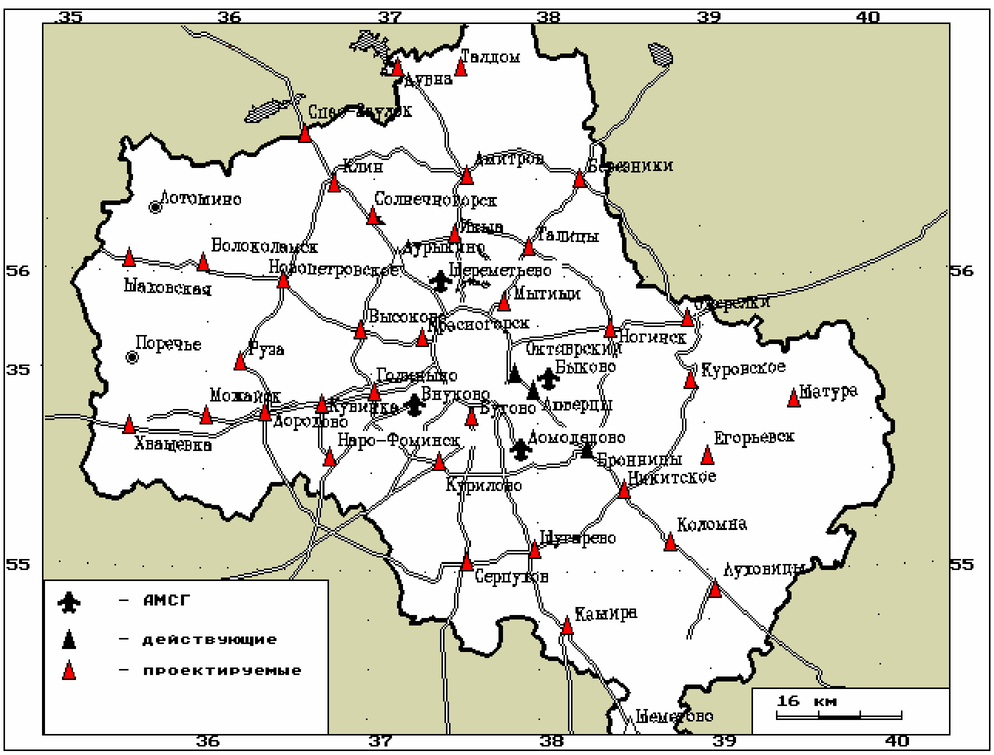

Fig. 5.1. Proposed efficient pattern of RWS arrangement (red triangles) over Moscow Region.

The northernmost zone IV will be the next by network density. In the rest of the climatic zones of the region the density will be lower. In zone VI, the closest to the city, the density in the final version will be 7.71. Figure 5.1 shows the pattern of RWS arrangement over Moscow Region.

6. CONCLUSIONS. AN OPTIMAL OBSERVATIONAL SYSTEM

With the aforesaid in mind, assuming a 20% error to be acceptable, we infer that 38-40 stations will be enough to begin with in creating an optimal-density RWS network, distributing the stations over Moscow Region in accordance with the type of relief (Section 5).

Another aspect of network optimization concerns the total expenditure composed of the maintenance costs and losses caused by data uncertainty. The expenditures may be large in two cases: 1) with a too dense and thus too costly to maintain network and 2) with no network available and thus no expenditures, but with losses due to lack of data. Lump sum expenses of setting up and maintaining the network would increase the first summand, while losses due to observational data uncertainty and insufficient use of information would increase the second one.

Hence the totality of parameters accounting for the network costs and losses due to observational uncertainty in which the net amount of costs and losses is the least. It is this totality that determines observational system efficiency. Paper [4] presents a straightforward pattern to implement this approach. With all the other parameters being fixed, all weather parameter uncertainties and losses thus entailed prove only to depend on the network density and will become a decreasing function of the frequency of stations on the network. It should be remembered that theoretically [4], [5] the benefit from using meteorological data provided by observational stations, beginning from a certain number of the stations, n, increases but negligibly compared to the linear increase of the network maintenance expenses.

Practical realization of the economic approach to network planning in this simplified scheme is very difficult to achieve due to present-day insufficient knowledge of the economic consequences of using meteorological information. To develop this approach, economic considerations should be involved. That is why we only examined this problem in terms of meteorology. Meteorological data uncertainty was assumed to be fixed and was allowed for in working out the requirements for RWS network density. The number of stations, n, thus obtained is considerably dependant on the assumed root-mean-square error in the data to be employed, while the approach itself is not indicative of the root-mean-square error to be chosen. The choice was governed by the estimates commonly accepted in such applied problems, rather than by economic considerations.

7. REFERENCES

[1] Alibegova, Zh. D. 1985. *Space and time structure of liquid precipitation fields*. Gidrometeoizdat, Leningrad. 230. (In Russian)

[2] Bezrukova, N.A. 1991. *The peculiarities of frontal precipitation field morphology*. Trudy CAO. 178: 47-60. (In Russian)

[3] Berulev, G.P., Bratushenko, V.D., Evrpiakov, V.A., Melnichuk, Yu.V. and Chernikov, A.A. 1981. *An automated radar system to measure atmospheric precipitation*. Trudy V All-union conference on radio meteorology. Moscow, Gidrometeoizdat. (In Russian)

[4] Gandin, L.S. and Kagan, R.L. 1976. *Statistical methods of interpreting meteorological observational data*. Gidrometeoizdat, Leningrad. 359. (In Russian)

[5] Gandin, L.S. and Kagan, R.L. *Economic aspects of meteorological network planning*. Trudy MGO. 208: 120-131. (In Russian)

[6] Gushina, M.V. and Kagan, R.L. 1966. *On the statistical structure of precipitation fields*. Trudy MGO. 191: 35-46. (In Russian)

[7] Drozdov, O.A. 1936. *A method of creating meteorological network on a plain terrain*. Trudy MGO. 12: 10-112. (In Russian)

[8] Drozdov O.A. 1961. *On principles of improving weather station network*. Trudy MGO. 123: 33-46. (In Russian)

[9] Drozdov, O.A. and Shepelevsky, A.A. 1946. *The theory of interpolation in a stochastic field of weather elements and its application in weather mapping and network improvement*. Trudy NIU GUGMS. I. 13: 65-115. (In Russian).

[10] Kagan, R.L. 1966. *On estimation of rain gage data representativeness*. Trudy MGO. 191: 22-34. (In Russian)

[11] Litvinova, I.V., Pavlova, I.S. and Polischuk, A.I. 1968. *Some data on winter precipitation fields*. Trudy MGO. 230: 60-64.

[12] Polischuk, A.I. *On the statistical structure of winter precipitation fields*. Trudy MGO, 1968, v. 215, p. 153-156. (In Russian)

[13] Stulov, E.A. 1994. *The effect of mesoscale relief irregularity on frontal precipitation fields*. Meteorologia i Gidrologia. 3: 20-30. (In Russian)

[14] Stulov, E.A. 1997. *Estimation of orographic rainfall enhancement caused by mesoscale topographical inhomogeneities*. Meteorology and Hydrology. 5: 27-35. (in Russian).

[15] Bezrukova, N.A., Dunkel G. *Implementation Plan for Road Weather Information System*. Tacis Report 7.1. Federal Highway Administration of Russia 1997.

ACKNOWLEDGEMENT

The authors are thankful to M.A. Khanchina for the adequate rendering of the contents of this paper in English.