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DEA-BASED DYNAMIC ASSESSMENT OF REGIONAL ENVIRONMENTAL EFFICIENCY

Abstract

We apply window Data Envelopment Analysis (DEA) to the solution of the problem of assessment of the efficiency of regional production systems in Southern Russia. The proposed method allows to monitor the changes in efficiency of regional economic systems throughout time and has a high discrimination power. The simplicity of the technical implementation of the proposed method and the availability of the necessary software for its use allow one to hope for its wide implementation in the modern practice of regional environmental management.

1. INTRODUCTION

Data Envelopment Analysis (DEA) currently represents a developed methodology for comparative evaluation of efficiency of different production facilities using a wide range of input and output parameters. Efficiency, in the context of DEA, is the ratio of the weighted sum of production outputs (that is to say, production results such as volumes of produced goods) to a weighted sum of inputs (resources consumed), which allows to classify decision making units (DMUs) as effective only if they produce the maximal possible outputs with the minimal possible inputs (Charnes, Cooper and Rhodes, 1981).

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Basic and modified data envelopment analysis models have been successfully employed to solve a wide variety of practical management tasks, from forming company or regional ratings, as well as ratings for innovative scientific programs to choosing optimal ways to increase the efficiency of DMUs which are currently ineffective (Khrustalev and Ratner, 2015a,b; Melnikov, 2016; Carrillo and Jorge, 2016). DMUs can represent both individual agents and some kinds of integrated formations such as corporations, clusters or regional economic systems, as long as their activities can be represented with the same sets of inputs and outputs.

One of the main factors that led to DEA becoming popular as a research method is availability of various software that allows to decrease the complexity of solving real-world problems to a minimum. Some freely available packages include DEA Frontier, MaxDEA, Open Source DEA, et al. They allow to use input- and output-oriented radial models with constant and variable return-to-scale. However, some more complex DEA options, such as those that allow to research efficiency of DMUs dynamically, are implemented as paid options in the aforementioned packages.

The most commonly used method involves calculating the Malmquist index (Malmquist, 1953; Fare et al., 1994). In contrast to a simple comparison of efficiency coefficients for each DMU during the times t and $t+1$ (which are calculated by solving two separate DEA problems), using the Malmquist index allows to also consider the change in the efficiency frontier itself, which can happen sometime during the period between t and $t+1$. In this case, the complexity of the problem and the volume of necessary calculations greatly increase.

To overcome these difficulties and to reduce the problem of monitoring the efficiency of objects dynamically down to solving two or more basic DEA models, one can use an approach known as "window analysis" (Charnes et al., 1985), which is similar to the moving average method. The idea of this method is to select a "window" for each DMU of width w, for example, $w=4$ for quarterly production data. Then each set of input and output data between 1 and w represents a single DMU, that is to say, the problem of evaluation efficiency is solved for $w \times n$ "DMUs", and for each real DMU w efficiency coefficients are calculated. The window is then moved by one observation to the right and w efficiency coefficients are re-calculated again for each DMU. In the end, one can use a simple arithmetic mean of the efficiency coefficients calculated for the specific time with different windows as the dynamic measure of efficiency. This approach allows for robust efficiency measurement and finding trends in DMU efficiency changes while remaining within the framework of basic DEA models that are freely available.

We test window analysis method while solving a problem of comparative ecologic&economic efficiency evaluation for regional economic system (RES). A static case was considered in (Ratner, 2016), where efficient regions are those that produce the most useful economic and social effects (interpreted as GRP and population) with minimal negative environmental impact (air, water and soil pollution). This paper presents a dynamic case of the same problem.

We solve the problem of monitoring efficiency of RES dynamically by calculating efficiency coefficients for each RES using window analysis with varying window widths. Comparing these results allows to conclude that using the maximal window width for window analysis is preferable both from the computing and content points of view.

2. METHODOLOGY

2.1. Basic environmental DEA model for assessment regional ecology management system's efficiency

Let's consider the task of evaluating ecologic and economic efficiency of regional economic systems (RES) using a set of indicators for the time period *T*. To do so, we need to use a basic input-oriented ecologic DEA (EDEA) model (Fare and Grosskopf, 2004) for each moment *t* in *T*. The difference between EDEA and traditional DEA lies in the presence of unwanted outputs. For each $t \in (1, \ldots T)$ we'll represent each RES as a DMU that uses various resources (energy, raw materials, labor, capital, etc.) as inputs and an economic result as an output. This can be measured with a variety of widely-used indicators, such as the GRP, gross value added, population's levels of income, etc. Furthermore, each DMU also outputs negative ecologic effects as an unavoidable result of economic activity: atmosphere pollution, solid waste, waste water, etc. For each RES_t, we look for a way to reduce the inputs (use of resources) and unwanted outputs (negative ecologic effects) without reducing desirable outputs (economic results). DMUs that produce maximal results with minimal negative ecologic effects and resource consumption during the moment *t* are considered effective.

This problem can be formalized thusly. Let there be *K* homogenous DMUs, each of which is defined with *N* inputs and *M* outputs. Outputs 1, 2, … *p* are desirable (useful results) and outputs *p*+1, *p*+2, …, *M* are undesirable (negative effects).

In the coefficient form, the problem of evaluating the efficiency of the 0-th DMU in moment t can be written down as:

$$\max_{u,v} \sum_{m=1}^{M} u_m y_{m0}^{t} \qquad (1)$$

s.t.

$$\sum_{m=1}^{M} u_m y_{mk}^t - \sum_{n=1}^{N} v_n x_{nk}^t \le 0 \quad k = 1,2,\cdots K,$$

$$\sum_{n=1}^{N} v_n x_{no}^t \; = 1,$$

$$u_m, v_n \ge 0 \quad m = 1,2,\dots M \quad n = 1,2,\dots N;$$

where: $X^t = (x_{10}^t, \dots x_{No}^t) \ge 0$ is a vector of inputs for the moment *t* of size *N*,

$Y^t = (y_{1o}^t, \dots y_{Mo}^t) \ge 0$ is a vector of outputs for the moment *t* of size *M*,

K is the number of DMUs,

u_m, v_n are unknown non-negative weights that need to be determined.

For each DMU, we solve a rational linear programming task to maximize the following:

$$h = \frac{\sum_{r=1}^{p} \mu_r y_{ro}^t - \sum_{s=p+1}^{N} \mu_s y_{s0}^t}{\sum_{i=1}^{M} v_i x_{io}^t}, \tag{2}$$

s.t.

$$\frac{\sum_{r=1}^{p} \mu_r y_{rj}^t - \sum_{s=p+1}^{N} \mu_s y_{sj}^t}{\sum_{i=1}^{M} v_i x_{ij}^t} \le 1$$

The ratio (2) is called the momentary efficiency measure for ecologic and economic efficiency of a DMU. DMUs that have this coefficient equal to 1 in moment *t* are effective, and the others are not. After calculating efficiency coefficients for every RES for each $t \in (t_1, \dots T)$, we can examine the trends of the resulting dynamic series.

Undesirable outputs can simply be viewed as inputs; thus the momentary efficiency measure becomes:

$$h^* = \frac{\sum_{r=1}^{k} \mu_r y_{ro}^t}{\sum_{i=1}^{M} v_i x_{io}^t + \sum_{s=k+1}^{p} \mu_s y_{so}^t}, \tag{3}$$

Well known study of Korhonen and Luptacik (Korhonen and Luptacik, 2004) proves that the ecologic and economic efficiency *h* и *h** are equivalent and can both be used to solve basic CCR models, while other authors (Ratner, 2016; Khrustalev and Ratner, 2015a; Khrustalev and Ratner, 2015b; Fare and Grosskopf, 2004) show that in a simple case, undesirable outputs can be used as the only inputs for a model.

This interpretation of undesirable outputs is quite justified when solving a problem that doesn't require tracking the efficiency of each type of resource used by the RES (Ratner, 2016; Khrustalev and Ratner, 2015b). This simplified version of the problem marks the DMUs that produce the maximal social and economic results with the minimal negative ecological effects as efficient. The set of these DMUs defines a hyperplane of a convex multifaceted cone. DMUs that have efficiency coefficients below one can have their inputs proportionally reduced to move closer to the efficiency barrier: $(X_0^t, Y_0^t) \Rightarrow (hX_0^t, Y_0^t)$ (Cook and Seiford, 2009).

One can obtain an efficient point from the original one using the slack variables $S^+(s_1^+, \dots s_N^+)$ and $S^-(s_1^-, \dots s_M^-)$ by performing a shift $(hX_0^t - S^-, Y_0^t + S^+)$. These slack variables are determined during the second stage of solving the optimization problem and are interpreted as the potential decrease for negative ecologic effects. Some sources call this step of calculating the additional variables a "goal-setting method" (Bian et al., 2013), since the calculated potentials are the goals for each DMU's efficiency. Using dynamic series for each of the target parameters also gives a lot of additional information for DMUs in ecologic management and economic systems.

2.2 Dynamic environmental DEA model for assessment regional ecology management system's efficiency

Window analysis is a widely-used method for evaluating changes in DMU efficiency throughout time. This method allows to compare the DMU being examined not only with other DMUs but also with itself in other time periods. To do so, each of the K DMUs is represented as a set of *T* homogenous DMUs $\mathrm{DMU}_i^{t_1}, \mathrm{DMU}_i^{t_2} \dots \mathrm{DMU}_i^T$, defined by inputs $X_i^{t_1}, X_i^{t_2}, \dots X_i^T$ and outputs $Y_i^{t_1}, Y_i^{t_2}, \dots Y_i^T$. The DEA problem (1) is then solved *T*-*w*+1 times for *K*×*w* (*w*≤*T*) DMUs (or, in the context of these research, regions) $\mathrm{DMU}_1^{t_j}, \mathrm{DMU}_1^{t_j+1}, \dots,\ \mathrm{DMU}_1^{t_j+w}, \dots \mathrm{DMU}_K^{t_j}$, $\mathrm{DMU}_K^{t_j+1} \dots \mathrm{DMU}_K^{t_j+w}$.

The first time, problem (1) is solved for the time interval of $t_1, \dots t_1 + w$. Let us define this interval as w_1. Solving this problem $\forall \mathrm{DMU}_i$ we calculate *w* coefficients of momentary efficiency $h^{t_1}(X_i^{t_1}, Y_i^{t_1}),\ \ h^{t_1+1}(X_i^{t_1+1}, Y_i^{t_1+1}), \dots, h^{t_1+w}(X_i^{t_1+w}, Y_i^{t_1+w})$, that correspond to $\mathrm{DMU}_i^{t_1}, \mathrm{DMU}_i^{t_2} \dots \mathrm{DMU}_i^{t_1+w}$

The window is then moved by one interval to the right. The second time we solve the problem using the window of w_2: $t_2, \dots t_2 + w$ we get the momentary efficiency coefficients $h^{t_2}(X_i^{t_2}, Y_i^{t_2}),\ \ h^{t_2+1}(X_i^{t_2+1}, Y_i^{t_2+1}), \dots, h^{t_2+w}(X_i^{t_{21}+w}, Y_i^{t_2+w})$.

Moving the window continues until $t=T-w+1$, and, as a result of that, for each DMU_i^t, except for $\mathrm{DMU}_i^{t_1}$ and DMU_i^T, multiple momentary efficiency coefficients are calculated using different windows. Thus, $\mathrm{DMU}_i^{t_2}$ corresponds to two momentary efficiency coefficients $h_{w_1}^{t_2}$ and $h_{w_2}^{t_2}$, $\mathrm{DMU}_i^{t_3}$ to three: $h_{w_1}^{t_3}, h_{w_2}^{t_3}$ and $h_{w_3}^{t_3}$, etc. The final value of the momentary efficiency coefficient is the arithmetic mean for various windows:

$$h^t{}_{avr} = {}^1\!/_q \sum_{j=1}^{q} h_{w_q}^t \,, \tag{4}$$

where q is the number of windows for which momentary efficiency coefficients have been calculated.

When solving problems of comparative evaluations for energy and ecology efficiency of DMUs, one often assumes that they use very similar production technologies (Wang et al., 2013). Then, the differences in efficiency of researched objects can be completely explained by management quality. This assumption places some restrictions on the window method, since production technologies can change overtime. Therefore, the window width should be sufficiently small to avoid comparing objects that use old technologies with objects that use newer and more efficient ones. Most researches that follow this assumption of unchanging production technologies, the value of 3 years is taken as the window width (Wang et al., 2013; Wu et al., 2014). However, in the problem of comparing ecologic and economic efficiencies of regional economic systems, this limitation is insignificant. We are interested in any change of ecologic or economic efficiency of a region, regardless of whether it’s caused by improved management, new technologies, environmental protection measures, or a change in regional economy system or energy system structure (Ratner and Nizhegorodtsev, 2017).

Another oft-discussed limitation of the window method is the stability of resulting efficiency coefficient evaluations. Some works, e.g. (Sueyoshi, 1992), suggest to use standard deviation to determine stability:

$$STD_i = \sqrt{\frac{\sum_{t=t_1}^{T} \sum_{k=1}^{T-w+1} (h_{i,w_k}^t - h_{avr}^t)^2}{w \times (T - w + 1)}} \tag{5}$$

Or, alternatively, the variation:

$$Var_i = \max(h_{i,w}^t) - \min(h_{i,w}^t) \tag{6}$$

Other authors, e.g. (Wu et all., 2014), use the range of efficiency coefficient values for different windows for each moment $t \in (t_1, \ldots T)$:

$$CR_i^t = \max(h_{i,w}^t) - \min(h_{i,w}^t) \tag{7}$$

Regardless of whether one uses the eq. (5), (6) or (7), the stability evaluation for the initial and final moments (t_1 and T) uses only a single value. For this reason, most authors simply omit these moments from their research and evaluate stability only within the research interval (Wang et al., 2013; Wu et al., 2014). This limitation can be overcome by using the "round robin" method, suggested by (Sueyoshi, 1992). The idea behind this method is that efficiency of each DMU is evaluated first only for t_1, then for (t_1, t_2), (t_1, t_2, t_3) and so on until $(t_1, \ldots T)$. This approach allows to obtain a better understanding of the dynamics of each DMU, including the issues of stability and presence of trends, however, this greatly increases the computational complexity of the problem.

Let us look at some advantages and disadvantages of the above-described methods for solving dynamic ecologic and economic efficiency evaluation problems for regional economic systems, using the Southern and North Caucasus Federal Districts during the period of 2010-2014 as an example.

3. RESULTS AND DISCUSSION

We describe each regional economic system with the following set of inputs and outputs:

x_{1i}^t – annual volume of pollution emitted into atmosphere from stationary sources (thousands of tons),

x_{2i}^t – annual volume of pollution emitted into atmosphere from automobile transportation (thousands of tons),

x_{3i}^t – annual volume of unfiltered wastewater discharge (millions of cubic meters),

x_{4i}^t – annual volume of insufficiently filtered wastewater discharge (millions of cubic meters),

x_{5i}^{t} – annual volume of industrial and household waste generation (millions of tons),

x_{6i}^{t} – annual volume of fresh water use from surface and underground bodies (millions of cubic meters),

y_{1i}^{t} – annual volume of gross regional product in 2010 prices (millions of rubles),

y_{2i}^{t} – regional population (thousands of people).

The aforementioned indicators were selected on the one hand due to their logical sufficiency and, on the other hand, due to their availability. Using a representative set of inputs and outputs for modelling ecologic and economic efficiency of regional economic systems allows to analyze more aspects. However, in the event that the amount of used inputs and outputs is close to the amount of DMUs or surpasses that, DEA stops being able to sufficiently discriminate efficiencies (Wang et al., 2013; Wu et al., 2014), which is characterized by an unusually large share of efficient DMUs in the final solution. Therefore, the amount of inputs and outputs should not be excessive, and the inputs and outputs that are selected for use should be informative.

The Russian statistical accounting systems for ecologic aspects of the economy is currently undergoing major improvements. The yearly reports "On the state of environmental protection in Russian Federation" periodically cover the indicators of anthropogenic influence, with the method for their calculation improving over time. These reports can be found on the website of the Ministry of Natural Resources (www.mnr.gov.ru). For instance, the 2010 report differentiates the indicator of wastewater discharge into natural objects and introduces the indicator of regional freshwater consumption, as well as accounts for different methods of garbage disposal (recycling, burying), introduces several climate change indicators, etc. This approach allows to account for a larger number of ecologic indicators, but limits the possible observation periods to those times within which the system remained sufficiently similar.

The suggested set of input and output parameters was chosen based on the results of (Perlis, 2014; Forgione et all., 2016; Ratner and Ratner, 2016; Olejniczak and Lukasik, 2016; Nizhegorodtsev and Ratner, 2016; Verma et all, 2016, Wu et all., 2014). The efficiency coefficient was calculated for each region of the Southern and Northern Caucasus Districts with several methods: the point method, the window method with width equal to the entire observation period, window method with a width of 3 years, and window method with a width of 4 years. Results of the calculations for the point method are presented in Tab. 1, and in Tab. 2 for the window of 3 years.

Tab. 1. Values of ecologic and economic efficiency coefficients of southern Russian regions – calculated with the point method

Region	2010	2011	2012	2013	2014
Adygeya Republic	1	1	1	1	1
Kalmykia Republic	1	1	1	1	1
Krasnodar Region	1	1	1	1	1
Astrakhan Region	1	1	1	1	1
Volgograd Region	1	1	1	1	1
Rostov Region	0.987	1	1	0.988	0.791
Dagestan Republic	1	1	1	1	0.871
Ingushetiya Republic	1	1	1	1	1
Kabardino-Balkar Republic	1	0.864	1	1	0.571
Karatchayevo-Tcherkess Republic	0.801	0.774	0.700	0.630	0.551
Northern Osetiya-Alaniya Republic	0.809	0.858	0.760	0.797	0.473
Tchetchen Republic	1	1	1	1	1
Stavropol Region	0.930	0.848	0.876	0.993	1

Tab.2. Values of ecologic and economic efficiency coefficients of southern Russian regions – calculated with a window width of 3 years

Region	2010	2011	2012	2013	2014
Adygeya Republic	1	1	1	0.872	1
Kalmykia Republic	1	1	1	1	1
Krasnodar Region	1	1	1	1	1
Astrakhan Region	0.865	0.740	0.898	1	1
Volgograd Region	0.906	1	1	1	1
Rostov Region	0.807	0.893	1	0.968	0.759
Dagestan Republic	1	0.955	1	1	0.756
Ingushetiya Republic	1	1	1	1	1
Kabardino-Balkar Republic	0.705	0.729	1	0.945	0.569
Karatchayevo-Tcherkess Republic	0.680	0.639	0.693	0.597	0.534
Northern Osetiya-Alaniya Republic	0.712	0.761	0.758	0.792	0.473
Tchetchen Republic	1	1	1	1	0.925
Stavropol Region	0.768	0.789	0.835	0.883	0.855

Analyzing the results shown in tables above, we conclude that the ecological and economic efficiency of most southern Russian regions is quite high. The highest efficiency indicators belong to the Adygeya, Kalmykia, Ingushetia and Tchetchen Republics, as well as the Krasnodar region, and the lowest indicators manifest in Karatchayevo-Tcherkess Republic as well as the Northenr Osetiya-Alaniya Republic.

As was expected, the window method has a higher discrimination rate due to the fact that the DEA problem is solved for 39 DMUs (for *w*=3) rather than the 13 in the point method. Using the window method, we can see that only three regions of Southern Russia remained effective during the entire observation period: Kalmykia and Ingushetiya republics as well as the Krasnodar region.

To obtain more detailed conclusions we need to perform a comparative analysis of results for individual regions with different window widths (*w*=5, 3, 2) as well as the point method (fig. 1-2). It's easy to note that using the maximal window width (the entire observation period) leads to minimal coefficient values for non-effective objects, which allows for easier comparison among them.

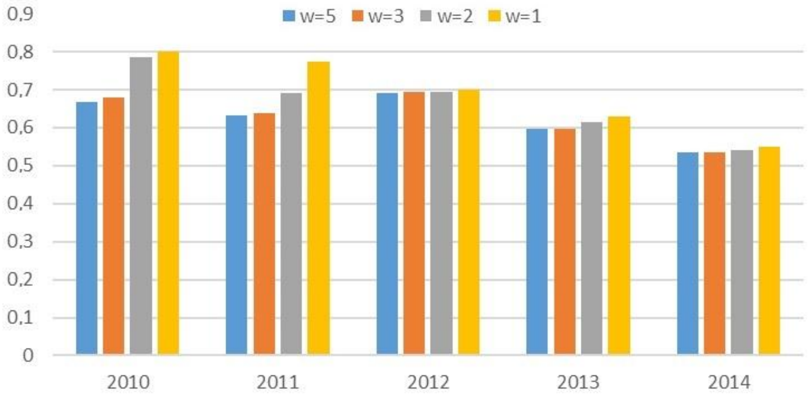

Fig. 1. Comparing the ecologic and economic efficiency of Karatchayevo-Tcherkess Republic over time with different methods and window widths

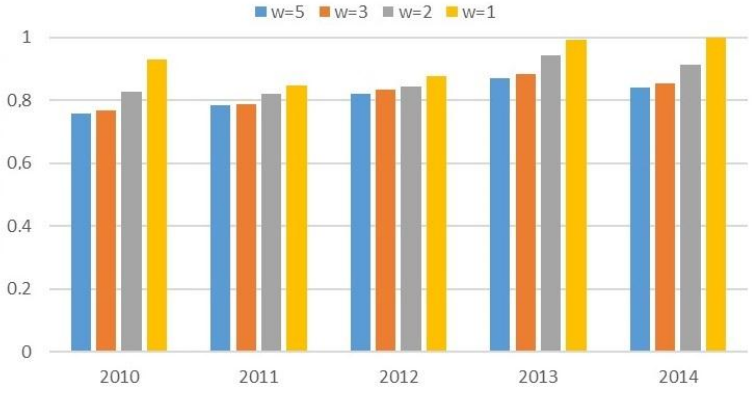

Fig. 2. Comparing the results of ecological and economic efficiency of Stavropol region over time with different methods and window widths

Narrower windows lead to higher efficiency coefficients. We would like to note that the direction in which dynamics of DMU efficiency change (i.e. whether they drop or rise) can also differ throughout various methods. For example, analyzing the dynamics of efficiency in the Karatchayevo-Tcherkess Republic using the point method, one can notice a decrease. This implies that the efficiency of this republic worsens over time compared to other regions. However, using a window width equal to the observation period will show that there's no particular trend in these dynamics. That is to say, efficiency of the region will sometimes rise and sometimes drop, showing a lack of a coherent ecologic policy in this region. No particular trends show up with window widths of 3 and 2 years for this region either.

Comparing the stability of efficiency evaluations with different window widths (eq. 5), we can point out that the standard deviation for most regions changes insignificantly.

Tab. 3. Standard deviation of evaluations of ecologic and economic efficiency of southern Russian regions with varying window widths

Region	***STD, w*=5**	***STD, w*=3**	***STD, w*=2**
Adygeya Republic	0.0684	0.0564	0.0444
Kalmykia Republic	0.0009	0.0000	0.0000
Krasnodar Region	0.0000	0.0000	0.0000
Astrakhan Region	0.1534	0.1173	0.0777
Volgograd Region	0.0520	0.0314	0.0000
Rostov Region	0.1038	0.0895	0.0823
Dagestan Republic	0.1055	0.0805	0.0836
Ingushetiya Republic	0.0000	0.0000	0.0000
Kabardino-Balkar Republic	0.1881	0.1636	0.1547
Karatchayevo-Tcherkess Republic	0.0615	0.0560	0.0789
Northern Osetiya-Alaniya Republic	0.1294	0.0990	0.1154
Tchetchen Republic	0.0333	0.0248	0.0233
Stavropol region	0.0445	0.0424	0.0626

The most stable indicators with varying window widths throughout the entire period are demonstrated by the regions that have the highest efficiency values, as is to be expected. These regions are the Ingushetiya, Kalmykia and Tchetchen Republics, as well as the Krasnodar and Volgograd regions. The most notable changes in stability, depending on window widths, can be observed only in the Astrakhan region and the Northern Osetiya-Alaniya Republic. Therefore, it is difficult to judge which window width is more appropriate for increased stability of the results.

4. CONCLUSIONS

The main result of the paper is the adaptation of the window method to the tasks of monitoring the complex ecological and economic efficiency of the regional production systems dynamically. In contrast to simply solving unrelated problems of estimating the comparative effectiveness of RES at any particular point of time in the research period, the window method allows us to reveal the dynamics of efficiency associated with the shift in the efficiency frontiers of the entire set of DMUs under consideration due to technological eco-innovations (the best available production technologies) or a change in the structure of the region's economics.

Estimates of the ecological and economic efficiency of RES calculated with a window of the maximum width equal to the entire observation period make it possible to discriminate the RES's in the best way.

The simplicity of the technical implementation of the proposed method and the availability of the necessary software for its use allow one to hope for its wide implementation in the practice of regional environmental management.

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