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Spatial modeling of the climatic water balance index using GIS methods

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Abstract—The aim of this study is to find the optimal spatialization method to model spatial differentiation of the climatic water balance (CWB). Monthly mean values from the period 1986–2010 for air temperature and precipitation as well as monthly solar radiation totals over Poland were considered in the study. Potential evapotranspiration data were calculated via the Turc formula.

Two simultaneous methods were used in the modeling: simple and multiple linear regression (with latitude, altitude, and distance from the coastline as variables) and the map algebra method. Map algebra was shown to be the better spatialization method; however, its optimization would require a reduction in the research scale and the use of more in-situ data. This would allow more local variables such as landform and land cover to be included in the analysis.

Key-words: spatial analysis, regression model, map algebra, climatic water balance, Poland

1. Introduction

Geographic information systems (GIS) provide a variety of methods for the modeling and presentation of data. GIS provides a powerful research tool for climatology and meteorology, where detailed analysis at different temporal and spatial scales is essential in order to understand processes prevailing in the atmosphere. Although temperature and precipitation have received the most attention in GIS research, increasingly complex meteorological and climatological indices are also under examination, as they provide information useful in the environmental and social sciences (*Tveito et al*., 2008).

One such index is the climatic water balance (*CWB*). It focuses on the difference between precipitation (*RR*) and evapotranspiration (*ETP*), presenting a basis for a climatic assessment of water resources in a given geographic area. An understanding of the spatial distribution of the climatic water balance appears to be very important to its comprehensive application in spatial management, agriculture, and hydroclimatological modeling.

Although the *CWB* index seems to be quite simple to compute, it is dependent on many different variables such as solar radiation, relief, land use, and urban development, among others. This creates certain difficulties. It is, first and foremost, a subject involving evapotranspiration, which varies considerably with changes in the natural environment. As data availability is poor, issues arise with proper index interpretation, mainly due to spatial differentiation.

GIS techniques enable the merging of different data processing and integration methods with complex analyses and modeling methods. However, given the complicated nature of the subject, it is no wonder that there exist many GIS methods that attempt to model the spatial differentiation of evapotranspiration (e.g., *Nováky*, 2002; *Xinfa et al*., 2002; *Fernandes et al*., 2007; *Vicente-Serrano et al*., 2007). Remote sensing techniques are also becoming more commonly used to address this research issue and is often used to supplement ground-based observations (*Rosema*, 1990; *Kalma et al*., 2008).

The purpose of this paper is to describe a new methodology for climatic water balance index implementation using geographic information systems (GIS) in cases when there is no appropriate spatial information given from in-situ observations.

The area under consideration is the territory of Poland, located in Central Europe. Poland was chosen because of its relatively diverse relief from the north (Baltic Sea coast) to the south (the Carpathians), which impacts weather and climate conditions. The lie of the land as well as the country's location suggest that an analysis based on the study area (Poland) seems to be representative of the greater region, e.g., Central and Eastern Europe.

2. Data and methodology

As mentioned before, evapotranspiration seems to be the crucial element of climatic water balance index calculations. Regrettably, the complexity of the process (caused by many factors) makes it very difficult to obtain exact values of *CWB* for current meteorological analyses. The alternative solution, the value of ETP, can be calculated to a high degree of precision with the use of simplified models including meteorological elements that are typically observed by meteorological stations. Therefore, analyses of the climatic water balance (CWB) are usually developed for regions where the input data, mainly air temperature and precipitation, can be readily obtained.

The research described herein is based on mean monthly values of air temperature and precipitation totals obtained from 60 meteorological stations as well as monthly totals for solar radiation obtained from 21 actinometric stations. The data cover the periods 1951–2010 and 1986–2010, respectively.

Not all the actinometric stations considered collect the necessary meteorological data, therefore, detailed analyses of the climatic water balance use data obtained only from 16 stations covering the period from 1986 to 2010.

Meteorological data were compiled using topographic information from the SRTM DEM model (*EROS,* 2011).

Given the limited nature of the source data, Turc formula (1961) was used to obtain potential evapotranspiration values. This method was confirmed (*Kowanetz*, 2000) to be suitable for describing the relationship between evapotranspiration and relief. The resulting formula is as follows:

$$CWB = RR - 0.4\frac{t}{t+15}I + 50 \,, \tag{1}$$

where RR is the monthly precipitation totals [mm], t is the monthly average air temperature [°C], and I is the monthly sum of total solar radiation [cal cm^{-2} day^{-1}].

Climatic water balance modeling was carried out using two approaches simultaneously. The first approach, examining correlations between environmental elements, used a linear regression method. Statistical relationships between CWB and geographic variables such as latitude, elevation, and distance from the coast line were taken into account. The second approach was based on data modeling implementing a map algebra procedure. The results of both approaches were validated using common error estimators.

The CWB values calculated for 16 stations were used as reference data (*Fig. 1*). In this study, climatic water balance modeling was conducted using the two methods simultaneously.

An analysis was conducted for the growing season, defined as the time period from May until October. This is consistent with what is frequently considered in agrometeorology.

2.1. Regression models: simple linear regression, multiple linear regression

As mentioned above, the first approach utilized regression models: simple linear regression (SLR) and multiple linear regression (MLR). Close relationships between climatic water balance and geographic factors became the basis for the model (*Wypych* and *Henek*, 2012), with longitude, latitude, elevation, as well as distance from the coast as explanatory variables.

Fig. 1. Location of the climatic water balance data source stations.

Due to the limited number of samples and also the smallest correlation (from all the analyzed predictors) coefficient between *CWB* values and longitude, it was finally decided to exclude longitude as a variable from regression models, Eqs. (2–4), and not use it in further analyses:

$$Z(s) = \beta_0 + \beta_2 H(s) + \varepsilon(s), \tag{2}$$

$$Z(s) = \beta_0 + \beta_1 \varphi(s) + \beta_2 H(s) + \varepsilon(s)\,, \tag{3}$$

$$Z(s) = \beta_0 + \beta_1 \varphi(s) + \beta_2 H(s) + \beta_3 d(s) + \varepsilon(s)\,, \tag{4}$$

where $Z(s)$ is the dependent variable, $\varphi(s)$ is the latitude, $H(s)$ is the elevation [m a.s.l.], $d(s)$ is the distance from the coast [m], and $\varepsilon(s)$ is the regression residuals.

CWB values were calculated for points on a grid with a spatial resolution of 1 km on the basis of the described linear relationships and using the described regression method.

Data interpolation using radial basis functions (RBF) was used in the final step of creating the climatic water balance spatial differentiation map. RBF is an interpolation technique, which takes into account general tendencies as well as local variability. Research conducted hitherto (*Wypych* and *Ustrnul*, 2011) has confirmed the suitability of RBF as a method for CWB index spatialization.

2.2. Map algebra

The second approach was based on a map algebra application. This type of model requires a process of raster data transformation using GIS tools.

For this study, map algebra was used to create the final CWB spatial differentiation map. First, a series of maps showing the spatial distribution of climatic water balance index components such as air temperature, precipitation totals, and solar radiation, were created using in-situ data.

Component maps of the climatic water balance index were constructed according to a method developed by international research teams dealing with GIS implementation in meteorology and climatology (*Dobesch et al.*, 2007). The method most widely used and commonly considered most effective is kriging (*Dobesch et al.*, 2007).

Temperature spatial differentiation maps were created as the first CWB component using the residual kriging method (*Ustrnul* and *Czekierda*, 2005). Several geographic parameters including elevation, latitude, longitude, and distance to the Baltic coast (for stations located within 100 km), were used as predictor variables.

Precipitation totals were interpolated for the territory of Poland using the kriging method (*Łupikasza et al.*, 2007).

A solar radiation surface was obtained by the application of Solar Analyst ArcGIS. All necessary information such as sunshine duration, altitude at the given location, radiation parameters (diffuse factor and transmittivity), as well as topographic factors such as slope, aspect, and shaded relief based on the SRTM was implemented. Because of element sensitivity to local conditions (astronomical, geographic, meteorological), a variety of different settings in the Solar Analyst application were tested to achieve satisfactory final results. In most cases, the diffuse factor and transmittivity were adjusted. For Poland, the diffuse factor approaches 0.5, while a transmittivity value of 0.4 may also be assumed. In-situ data were used as the reference for parameter selection and model estimation.

All of the layers created were used as input parameters for the potential evapotranspiration model in the Turc formula (air temperature and solar radiation map) and used along with the precipitation map to calculate the climatic water balance for the territory of Poland using the map algebra method. Transformations affected entire layers; all cells of the raster were used as variables. Raster cell values were changed due to previously cited formulas for potential evapotranspiration and the CWB index.

2.3. *Validation*

The final step was to validate the proposed methods. Due to the limited number of reference points and the use of several different interpolation methods (which are not the typical methods of spatial data interpolation), only simple statistical evaluation measures could be used. The first and most basic measure of model adjustment was the value of the correlation coefficient between the real (from in-situ measurements) and modeled data (R). In addition, bias (RE), percentage error (PE), and absolute error (AE) were calculated and used. Because of the limited number of reference points, it became impossible to evaluate the models using the most common validation methods used for interpolation. Neither cross-validation nor the method of independent sampling could be properly used in this case. However, the suggested estimation factors used for analyzing the results of spatial analyses conducted using different interpolation methods (*ESRI,* 2001) were implemented to assess average real spatial interpolation errors. These include errors for points gained in the first validation step: RMSE (root-mean square error), MPE (mean percentage error), MAPE (mean absolute percentage error). All the model adjustment measures were implemented in relation to values obtained at field measurement sites.

3. Results

Research has shown that the spatial differentiation of the climatic water balance in Poland in the growing season (May – October) amounted to less than –200 mm in the central part of the country and hundreds of millimeters in the high mountain regions of the Carpathians Mountains and the Sudety Mountains (*Fig. 2*).

Most of the territory of Poland is characterized by a moisture shortage. Positive moisture values are typical only in the southern highlands, foothills, and mountain areas (*Fig. 2*). In addition, the spatial distribution of the climatic water balance varies seasonally.

Nevertheless, a detailed analysis of the climatic water balance index distribution shows regional and local differences attributable to the spatialization method implemented as described below.

The regression models used in this research study have shown to be most strongly affected by elevation in a significant correlation. The predominant role of this predictor has been to influence the spatial differentiation of the climatic water balance index in Poland. However, regardless of the regression method, the belt-like distribution of *CWB* index values is still discernible. This pattern holds true mainly in the spring and summer months, but it is less visible in the autumn. The Baltic Sea also affects seasonal differences by limiting evapotranspiration – higher *CWB* values noted between July and October. In May and June, it was not shown to have an important effect.

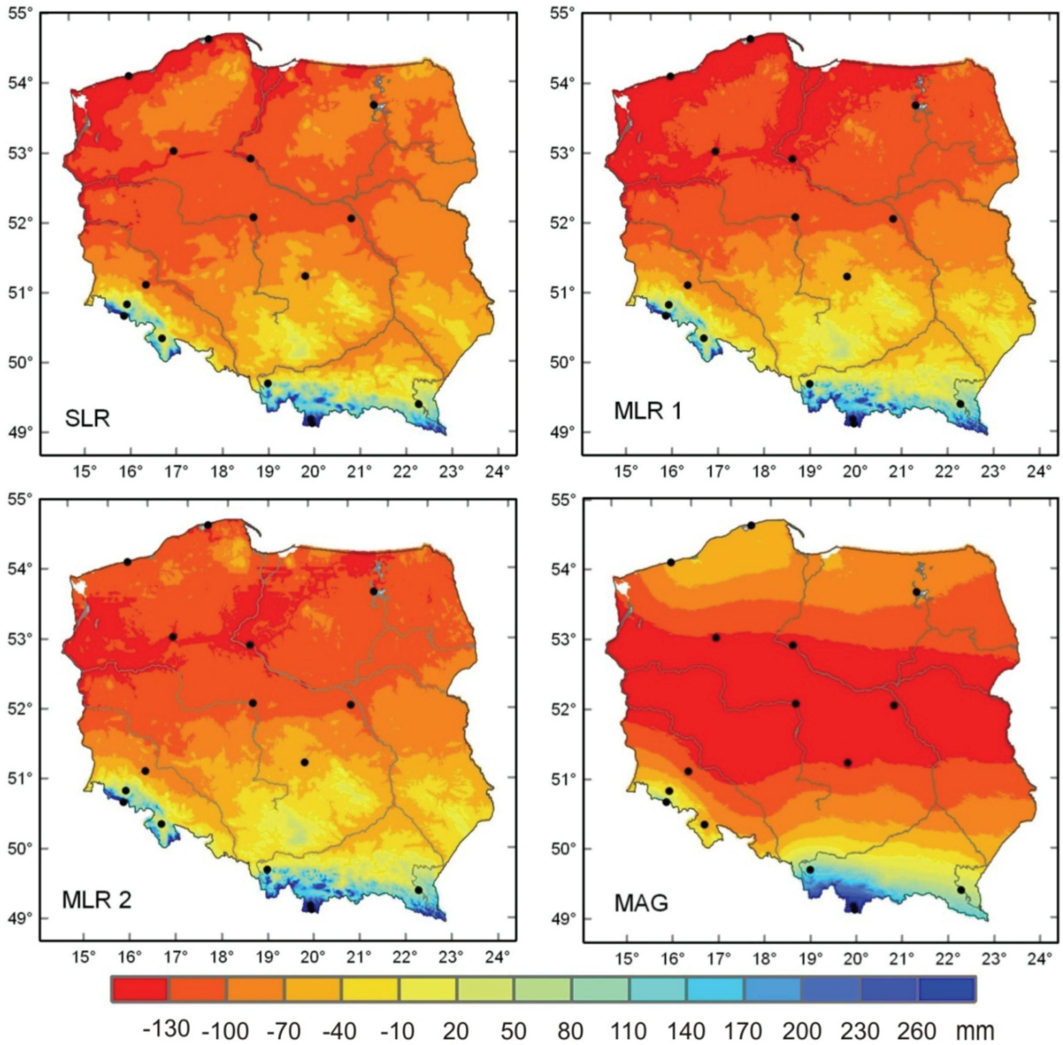

Fig. 2. Spatial differentiation of climatic water balance (*CWB* in mm) in Poland in the growing season (May–October) based on different methods.
SLR – simple regression: f (H), MLR 1 – multiple regression: f (φ, H), MLR 2 – multiple regression: f (φ, H, d), MAG – map algebra

With an understanding of the spatial differentiation of climate conditions in Poland, it can be stated that regression models can slightly deform *CWB* differentiation visualizations, especially in coastal areas, as mentioned previously.

When using the map algebra method (MAG), the belt-like distribution of the *CWB* shows that the index is dependent on geographic parameters such as elevation and latitude. The "distance from the Baltic coastline" variable is indirectly (i.e., by differentiation of temperature values and precipitation totals) implemented in the MAG model. The climatic water balance field shows a significant moisture deficit (the lowest *CWB* index values) in the lowlands of

Central Poland, whereas values estimated much higher than what other models produce can be observed along the coastline. This situation is characteristic of the entire growing season.

Fundamental evidence acknowledging and supporting the MAG approach can be used for a detailed analysis of *CWB* component spatial fields, which serve as the basis of this study. A MAG image is the effect of the spatialization of different elements such as precipitation and evapotranspiration, whereas the latter is a result of integrating solar radiation and temperature maps.

Research results produced using both methods were validated using universal statistical error estimators. *CWB* values calculated for the 16 weather stations considered in the study were used as reference data.

For all 16 weather stations considered, *CWB* values were calculated for the study period. For each point, the deviations of the modeled values were defined by subtracting the true values (*CWBmod – CWBcalc*) for the growing season (May–October) for each month separately. Positive error values (calculated differences) indicate model overestimation, whereas negative error values show undervaluation of predicted values.

Results for the growing period (May–October) clearly show that the map algebra (MAG) method gives the best fitting results in relation to the reference data. The highest (close to 1), correlation coefficient value confirms the best model adjustment. Absolute errors are also significantly smaller than those produced by other research methods (*Table 1*). The MAG model overestimates *CBW* values for northern and central Poland and produces the best predictions for the northeastern part of the country, and the least accurate predictions for the central part of Poland. For southern Poland, modeled values of the climatic water balance are lower than calculated values.

The differences reach an average in the tens of millimeters; however, in extreme cases, the model can give *CWB* index values different from true values by several hundred millimeters. This has been reported for the Kasprowy Wierch and Śnieżka mountain weather stations. Regression models not considering the distance from the Baltic coastline as a predictor (MLR 1) as well as simple regression (SLR) were shown to be the least accurate methods. The correlation coefficient is about 0.5 lower, and other estimators show minimally higher values in both cases (*Table 1*). It is worth noting that the spatial differentiation of the results produced by the methods used in this paper is readily observable. Simple linear regression (SLR) gives better results for areas near the Baltic coast and for the Sudety mountains in southern Poland. On the other hand, in the central Polish lowlands, differences between the methods used cannot be clearly distinguished. Finally, the MLR 1 method performs well in the Carpathian region.

Table 1. Climatic water balance values (*CWB*) with selected model errors at reference points in the growing season (May – October)

Reference stations	*CWB* [mm]	SLR		MLR_1		MLR_2		MAG	
		APE (%)	RE [mm]	APE (%)	RE [mm]	APE (%)	RE [mm]	APE (%)	RE [mm]
Kołobrzeg	–73.3	107.9	–79.2	17.5	12.8	146.1	–107.2	66.4	–48.7
Łeba	–69.4	122.0	–84.7	16.4	11.3	176.6	–122.6	88.9	–61.7
Piła	–155.4	19.5	30.4	14.2	22.0	12.4	19.3	12.4	19.3
Toruń	–160.9	21.7	35.0	13.3	21.4	14.5	23.3	14.5	23.4
Mikołajki	–97.6	1.4	–1.4	5.0	4.8	28.3	–27.6	28.3	–27.6
Koło	–181.8	38.6	70.2	9.5	17.3	39.3	71.5	39.3	71.5
Warszawa	–177.6	38.0	67.5	16.9	30.0	38.5	68.4	38.5	68.4
Legnica	–165.6	37.9	62.7	27.7	45.9	47.4	78.5	47.4	78.5
Sulejów	–157.9	52.8	83.4	13.3	21.0	60.5	95.5	60.5	95.5
Jelenia Góra	–16.1	117.2	18.9	46.7	–7.5	154.3	24.9	154.6	24.9
Śnieżka	271.1	40.7	110.2	55.3	–149.9	50.2	136.0	50.0	135.6
Kłodzko	–44.5	77.3	34.4	38.2	–17.0	139.0	61.8	138.9	61.8
Bielsko-Biała	165.2	88.4	–146.1	26.5	–43.8	75.8	–125.2	75.8	–125.3
Zakopane	378.5	39.7	–150.2	11.0	–41.7	37.0	–140.2	37.0	–140.2
Kasprowy Wierch	819.7	32.0	–262.4	35.7	–292.7	21.6	–177.1	21.5	–176.6
Lesko	86.5	87.5	–75.7	44.1	–38.2	56.0	–48.4	56.0	–48.5
MAE [mm]		82.0		83.0		75.5		48.6	
RMSE [mm]		102.5		95.3		88.3		86.1	
MAPE (%)		57.7		68.6		58.1		24.4	
R		0.940		0.937		0.950		0.988	

RE – bias, APE – absolute percentage error, MAE – mean absolute error, RMSE – root-mean-square error, MAPE – mean absolute percentage error, R – Pearson's correlation coefficient, MAG – map algebra, SLR – simple linear regression: f (H), MLR_1 – multiple linear regression: f (φ, H), MLR_2 – multiple linear regression: f (φ, H, d)

The least accurate results, regardless of method, were observed for Poland's mountain regions. All of the models predict values lower than real values for the Carpathians (*Table 1*). For the Sudety Mountains, significant positive differences were modeled only for Mount Śnieżka. Other weather stations are characterized by errors commonly found in the rest of the country. Coastal areas encountered the same difficulty as mountain areas when it came to the spatialization of the *CWB* index. Regression models significantly lower the prediction and estimate values close to those recorded for Poland's lake districts and the central part of the country.

As previously mentioned, map algebra images are produced by the spatialization of climatic water balance index components. Therefore, it could be supposed that the final map additionally contains some errors such as precipitation errors, and above all, potential evapotranspiration interpolation errors, since the latter were obtained using map algebra, where the temperature field was integrated with solar radiation. Moreover, solar radiation was modeled using the Solar Analyst tool, and the potential solar radiation field was based primarily on elevation.

4. Discussion

The climatic water balance is a complex index influenced by many different factors. These factors affect both precipitation and evapotranspiration values including solar radiation, relief and slope aspect, land use, and degree of urbanization.

In the course of research and analysis, several problems were identified that could potentially affect further research in this area.

Climatic water balance components such as precipitation and potential evapotranspiration are characterized by considerable spatial and temporal differentiation as well as strong correlations between atmospheric circulation, meteorological conditions, and local factors. Therefore, *CWB* spatial variability is difficult to identify. Current understanding of mesoclimate differentiation, especially that of mountain areas, suggests that many geographic variables should be taken into consideration. In order to accurately describe the spatial distribution of *CWB*, it is necessary to take into account variables such as slope, aspect, land use, and soil type, all of which determine how much solar radiation is available to produce given air temperature values (*Ustrnul* and *Czekierda*, 2005). Both solar radiation and air temperature affect the degree of evapotranspiration. Furthermore, both parameters must be calculated independently for smaller regions – especially regions characterized by specific mesoclimate conditions such as those found in coastal or mountain areas.

In order to determine the value of the *CWB* index, the magnitude of evapotranspiration must be properly estimated. Although Turc formula used in this paper is strongly correlated with geographic factors (especially elevation), it seems insufficiently sophisticated to fully represent evapotranspiration conditions. The purpose of this study was to identify the best spatialization method in a situation with a shortage of data; therefore, Turc formula was chosen as the least demanding. Ultimately, the final results do contain errors.

At least 30 years of daily data are needed in order to analyze the climatology of an element; in this case, the spatial and temporal differentiation of the climatic water balance. The data must address all *CWB* components. As mentioned before, no evapotranspiration data were available, and the available data required the use of complex formulas that are not completely suitable for long-term data. Furthermore, commonly used formulas providing potential evapotranspiration data only fulfill environmental requirements to a certain extent and tend to produce unreliable data (*Jaworski*, 2004).

The main objective of this research study was to depict *CWB* spatial differentiation using a limited quantity of homogenized data. Recent developments in GIS techniques have produced a wide range of powerful methods for capturing, modeling, and displaying of climate data. Using geospatial analysis seems to be the sensible response to the current research needs for this topic. Nevertheless, even the most advanced data processing methods we use contain failures and problems that need to be solved in order to perform detailed analysis of the climatic water balance index on different temporal and spatial scales.

Using only 16 reference points to create the regression models and validate the data, the results were error laden. The magnitude of the regression model errors cannot be accepted. The weather stations were not representative enough to build the final model. This is why, among other things, the land use factor was removed from the formula. In the regression methods, the most deficient were solar radiation data. It would be possible to use more reference points (however not so many as 60 stations as used for temperature and precipitation data), if modeled data were used instead of in-situ solar radiation data. There exist empirical formulas (*Podogrocki*, 1978) for which daily sums of total solar radiation are obtained using sunshine duration data.

It would also be possible to generate the missing data from, for instance, the Solar Analyst application. Nevertheless, the more generalized or simplified the data, the greater the possibility of error in the final model.

The data deficit problem also concerns the map algebra model and validation section. Model errors generated for “blank” areas (without measuring points) cumulate while being aggregated in the map algebra method. As far as estimating the models, weather stations located in the northeast and east of Poland, as well as in mountain areas are desirable.

The least accurate results were obtained for mountain areas. This is mainly because in the mountains weather systems are strongly affected by the topography, and the modeling of climate conditions requires representative points for different elevations, landforms, aspects, etc. The spatial resolution suggested for mountainous areas is at least one weather station per 1,300 km^2 for temperature, wind velocity, precipitation, and one weather station per 500 km^2 for snow data (*Barry*, 1992). The validation results for climatic water balance variability would be different (more positive) if the Kasprowy Wierch and Śnieżka weather stations were not taken into account. Model errors are also the effects of temporal/seasonal differentiation of particular climate elements included in the CWB index. Local factors are of great importance, especially in the spring and summer months, which is also reflected in the selected estimator values.

Regardless of the validation results, the obtained maps of climatic water balance spatial differentiation in Poland show certain problems with the methods used. Regression models are affected mainly by the lack of data used to create the formulas taking into account long-term and homogenous data series of necessary meteorological elements. The fundamental error source was the irregular location of the data gathering points and subsequently limited representativeness regarding various environmental conditions. This can be more clearly seen along the Baltic coast, but also in the northeastern part of Poland, and of course, in its mountains in the south. On the other hand, solar radiation field data seems to be the vulnerable point of the map algebra method. The limitations of the Solar Analyst application – mainly due to highly variable cloud cover – and the lack of a sufficiently dense network of weather stations failed to ensure good interpolation results.

5. *Conclusions*

The primary objective of this study was to find the optimal spatialization method to describe spatial differentiation of the climatic water balance (*CWB*) in Poland. Two different approaches employing five spatialization methods were used – regression models (simple linear regression, various multiple linear regression formulas) and map algebra. Climatic water balance values and their spatial distribution are dependent on both atmospheric circulation (i.e., weather conditions) and local environmental conditions. Hence, it was necessary to use many different geographic predictors including coordinates, elevation, and others.

The research confirmed that the application of GIS techniques is a useful and promising tool for constructing maps of different climate elements and indices. At the same time, through a detailed analysis of the research results, certain shortcomings of the proposed method can be reported. Aside from the nature of the method itself, the principal problem can be the lack of source data. As a consequence, there is the risk of performing extrapolation instead of interpolation.

The largest differences between model values and real values were noted for regions with a sparse weather station network. This means that the final results may be the effect of the particular method used in spatial analysis, especially for areas with few measuring points. Such cases warrant a very careful interpretation of the research results.

Regardless of the research method used, the obtained results confirm the role of local factors in CWB modification. Therefore, it is necessary to take into account not only the spatial scale, but also the time scale used for explanatory variables. This is because, depending on the area and the season, their impact on the predictand will vary.

No matter how accurate the results are, research experience and scientific intuition are the keys to the interpretation of research results. Careful and detailed analysis is required as well as thorough knowledge of pertinent physical processes and complexity of the geographic environment. Both types of factors need to be considered when choosing predictors and later in the course of model validation, where a complex series of explanatory variables is used.

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