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Spatial differentiation of the climatic water balance in Poland

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Abstract—Recent developments in GIS techniques have produced a wide range of powerful methods for capturing, modeling, and displaying of climate data. The main aim of the study was to identify an optimal interpolation method to describe the spatial differentiation of the climatic water balance in Poland based on meteorological data (temperature, precipitation, solar radiation) collected at 15 weather stations from 1986 to 2006. A climatic water balance index (*CWB*) was created based on a simplified definition, where it is interpreted as the difference between the precipitation total (*P*) and potential evapotranspiration (*PE*). The latter was calculated using the so-called Turc Equation. Four different spatial interpolation methods were used: (1) inverse distance weighting (IDW), (2) local polynomial (LP), (3) radial basis function (RBF), and (4) ordinary kriging. A subjective visual analysis of maps, root mean square error values, and coefficients of correlation indicated that the best *CWB* interpolation methods are the radial basis function method and the ordinary kriging method. However, spatial interpolation results suggest that the problem is more complex. Calculations performed for selected points of reference suggest that local geographic factors play an important role in the shaping of *CWB*. Such results also confirm the need to perform spatial climatic water balance analysis with special attention being paid to local conditions. Further research is needed that takes into account different temporal and spatial scales and aims to test established methods in other regions in Europe.

Key-words: spatial analysis, GIS, interpolation methods, climatic water balance, Poland

1. Introduction

Recent developments in GIS techniques have produced a wide range of powerful methods for capturing, modeling, and displaying of climate data. Advanced data processing methods allow for detailed analysis of climate elements on different temporal and spatial scales. GIS techniques designed to map temperature and atmospheric precipitation fields have received the most attention thus far. However, researchers are often interested not in the meteorological elements themselves but in the information that can be extracted from them in the form of various indices, which are useful in the environmental and social sciences (*Tveito et al*., 2008).

The *CWB* is a complex index that shows a climate-based assessment of the water resources in a given area. It focuses mainly on the difference between precipitation and potential evapotranspiration. Values of the index depend on many different variables such as solar radiation, relief, land use, and urban development. Spatial distribution of the climatic water balance appears to be very important in spatial management, agriculture, and hydro-climatological modeling. Since 2007, the Drought Monitoring System for Poland has been provided by the Institute of Soil Science and Plant Cultivation – State Research Institute in Pulawy. In the system, meteorological conditions that are causing drought are evaluated by the climatic water balance expressed by the difference between the precipitation and potential evapotranspiration (by Penman formulae). Nevertheless, it has not been the subject of detailed analysis thus far. Data covering any longer period is not readily available – especially evapotranspiration data – which creates the problem of index interpretation, especially due to its reliance on spatial differentiation. Therefore, the main aim of the study was to identify an optimal interpolation method to describe the spatial differentiation of the water balance in Poland taking into account a number of scale-based variables.

2. Source material and methods

Analyses of the climatic water balance are usually developed for regions where input data, mainly air temperature and precipitation, can be readily obtained from meteorological stations. The research presented herein is based on mean monthly values of air temperature as well as monthly solar radiation and precipitation totals. The data were obtained from 61 meteorological stations (temperature and precipitation) and 23 actinometric stations (solar radiation) for the 1951–2006 and 1986–2006 time periods, respectively. Not all meteorological stations collect actinometric data, which is why data was obtained from only 15 stations and covers the period from 1986 to 2006 (*Fig. 1*).

The climatic water budget was introduced into the research literature in the middle of 20th century by *Thornthwaite* (1948). He described the budget as the balance of precipitation, potential evapotranspiration, and actual evapotranspiration, taking into account both soil moisture utilization and soil moisture recharge (*Oliver* and *Fairbridge*, 1987). According to Thornthwaite and his colleagues (*Thornthwaite* and *Mather*, 1957), an average climatic water budget model can be expressed using two interrelated equations:

$$P = ET + S, \qquad PE = ET + D, \tag{1}$$

where P is the precipitation, ET is the evapotranspiration, PE is the potential evapotranspiration, S is the moisture surplus, and D is the moisture deficit. The first equation describes water inflow, outflow, and storage, and the second equation describes energy demands. The procedure designed by *Thornthwaite* and *Mather* (1957) to calculate climatic water balance parameters is still widely used in CWB research (e.g., *Kar* and *Verma*, 2005; *Tateishi* and *Ahn*, 1996).

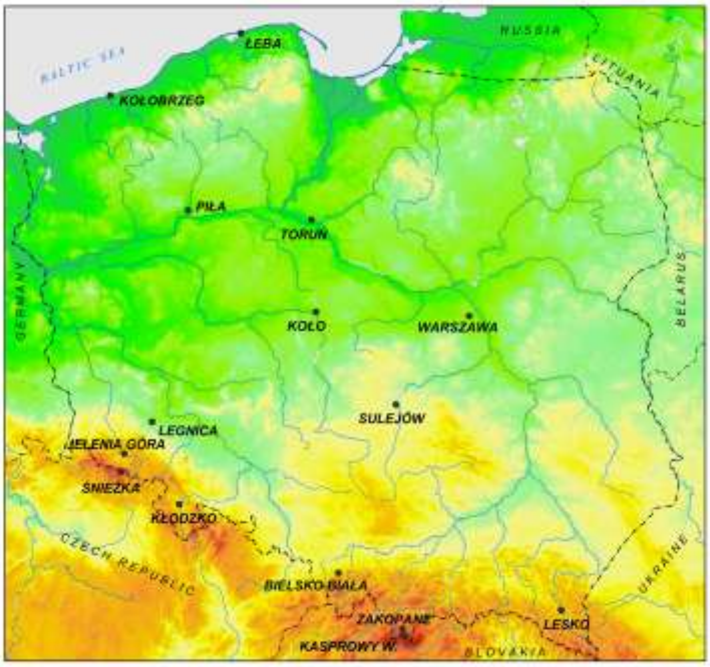

Fig. 1. Locations of the meteorological stations used in the research study.

Evapotranspiration process is the principal component of the climatic water balance, as it returns 60% to 80% of precipitation back into the atmosphere. In order to determine the value of the *CWB* index, the magnitude of evapotranspiration must be properly estimated. Owing to the difficulty of obtaining accurate field measurements, evapotranspiration is commonly computed from weather data using empirically derived formulas. A large number of more or less empirical methods have been developed over the last 50 years and are designed to estimate actual and potential evapotranspiration from different climatic variables. Some of the methods are only valid under specific climatic and agronomic conditions and cannot be applied under conditions different from those under which they were originally developed (*Allan et al*., 2004). As a result, the FAO Penman-Monteith Method is now recommended as the standard method for the definition and computation of the reference evapotranspiration, ET_o. The reference evapotranspiration provides a standard to which evapotranspiration at different periods of the year or in different regions can be compared (*Allan et al*., 2004).

The subject of *CWB* spatial interpolation is very complex. It is, first and foremost, a subject associated with the problem of the spatial interpolation of evapotranspiration, which varies considerably with changes in the natural environment. The second complexity has to do with the availability of data. Given the complicated nature of the subject, it is no wonder that there exist many methods that attempt to model the spatial differentiation of evapotranspiration (e.g., *Nováky,* 2002; *Xinfa et al*., 2002; *Kar* and *Verma*, 2005; *Loheide* and *Gorelick*, 2005; *Fernandes et al*., 2007). Remote sensing is becoming more commonly used to address this research issue and often supplements ground-based observations (*Woolhizer* and *Wallace*, 1984; *Rosema*, 1990; *Kalma et al*., 2008).

In Poland, most evapotranspiration and climatic water balance research is focused on the identification of a model that would best suit weather conditions in Poland. The following formulas were used in existing research: *Turc* (1961) method for potential evapotranspiration, *Bac* (1970) reference evaporation formulae for local index, and Penman modified to Polish conditions (*Sarnacka et al*., 1983). All three methods were applied to the analysis of the measurements data (Wild scale and GGI-3000 pan evaporimeter). Although the Turc method produced the largest differences between evapotranspiration totals measured *in situ* and values derived empirically (also shown by Hungarian research by *Nováky*, 2002), the method proved to be useful because of data availability issues. It was also selected because of other research that has shown that it is best at determining relationships with elevation (*Kowanetz*, 1998, 2000).

The climatic water balance index (*CWB*) was created based on a simplified definition where it is interpreted as the difference between the precipitation total (*P*) and potential evapotranspiration (*PE*). The final formula was the following:

$$CWB = P - 0.4\frac{t}{t+15} I + 50, \tag{2}$$

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

Given the limited nature of the source data (15 data points only) and the existence of strong relationships between potential evapotranspiration and geographic factors (the same is true for *CWB*), geographic parameter regression models were used to produce grid data consisting of annual *CWB* totals (CWB_{yr}) and vegetation period (April – September) *CWB* totals (CWB_{veg}) at a 0.2 degree spatial resolution (latitude and longitude). The resolution was chosen as the best for regional scale studies. Moreover, the DTM resolution of 250×250 meters was available for calculations. Simple and multiple regression models were used, taking into account the dependence of *CWB* on elevation above sea level

(H), longitude (λ), and latitude (φ). The following formulas were used to perform calculations:

$$CWB = f(H) + b, \quad CWB = f(H) + f(\lambda) + f(\varphi) + b, \qquad (3)$$

where b is the constant value.

Table 1 includes coefficients of correlation between geographic coordinates and *CWB* values on an annual as well as seasonal basis. The coefficients are very large – generally above 0.9 – and statistically meaningful at $\alpha = 0.05$. The coefficients of correlation tend to be somewhat larger when a multiple regression model is used. The value for the growing season is 0.95 and the value for the entire year is 0.94 (*Table 1*). The large size of the coefficient of correlation made it possible to use the regression method in order to calculate *CWB* for individual grids. The calculated values were then used in spatial analysis based on a variety of interpolation (spatialization) methods.

Table. 1. Coefficients of correlation (CC) between geographic parameters (H, φ, λ) and climatic water balance values (*CWB*) for the growing season (April – September) and for an entire year

CC (simple)	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Apr – Sep**	**Year**
H vs. CWB	0.95	0.91	0.91	0.90	0.90	0.86	0.92	0.92

CC (multiple)	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Apr – Sep**	**Year**
$H + \varphi + \lambda$ vs. CWB	0.97	0.94	0.92	0.92	0.91	0.89	0.95	0.94

There is a dearth of publications on optimal spatial CWB analysis methods, which has led to the testing of a variety of methods based on experiences with the interpolation of individual climate elements (*Dobesch et al.*, 2007; *Tveito et al.*, 2008). RMSE (root mean square error) analysis was used to assess the influence of interpolation methods on the analysis of spatial *CWB* differentiation. The source material available – 15 data points – was used as a source of reference. The relationship between results obtained during the spatialization process and values calculated based on field measurement data were also investigated.

3. Results and discussion

Four different spatial interpolation methods were used: (1) inverse distance weighting (IDW), (2) local polynomial (LP), (3) radial basis function (RBF), and (4) ordinary kriging. The first three are so-called deterministic methods. The fourth method, kriging, is used the most often and it is a geostatistical method.

Spatial interpolation was performed for different seasons and for the entire year, for Poland as a whole, using all four methods. RMSE values and coefficients of correlation as well as a subjective visual analysis of maps produced results that do not differ very much. However, the coefficient of correlation and RMSE suggest a somewhat more accurate interpolation based on RBF and kriging (*Table 2*).

Table 2. Validation results for different interpolation methods used in *CWB* calculations

Interpolation method (simple regression)	**Year**			**Vegetation period**		
	r	**RMSE**	**σ**	**r**	**RMSE**	**σ**
IDW	0.79	602	78	0.83	122	67
LP	0.83	683	207	0.87	186	177
RBF	0.84	641	145	0.88	147	125
Kriging	0.84	637	138	0.87	143	118
Interpolation method (multiple regression)	**r**	**RMSE**	**σ**	**r**	**RMSE**	**σ**
IDW	0.77	637	102	0.79	122	95
LP	0.83	710	196	0.75	177	174
RBF	0.84	673	144	0.86	141	131
Kriging	0.84	669	139	0.85	138	127

The *CWB* maps generated using the above methods can be found in *Figs. 2a,b*. The maps present annual *CWB* values as well as *CWB* values for the growing season (April – September). Differences between the annual spatial distribution and the growing season distribution are readily apparent. Annual *CWB* values range from 430 mm to 1200 mm, with maxima in the southern part of the country (mountains and uplands) and minima in the central part of the country (*Figs. 2a,b*). *CWB* fluctuates the most during the growing season (April – September), with positive values being recorded only in the mountains (up to 200 mm) and negative values (moisture deficit) across the rest of the country – as low as –230 mm in central Poland.

At the same time, *Figs. 2a,b* also show differences in spatial distribution resulting from the interpolation of input data using the simple regression method and the multiple regression method. *Table 2* shows validation results for the interpolation methods used in the study.

The interpolation results generated for Poland as a whole may be considered good, as the differences produced by different methods are small. However, a closer look at the problem on a local scale points to a great deal of complexity. Calculation results for different locations indicate that geographic influence is a factor that does affect *CWB*.

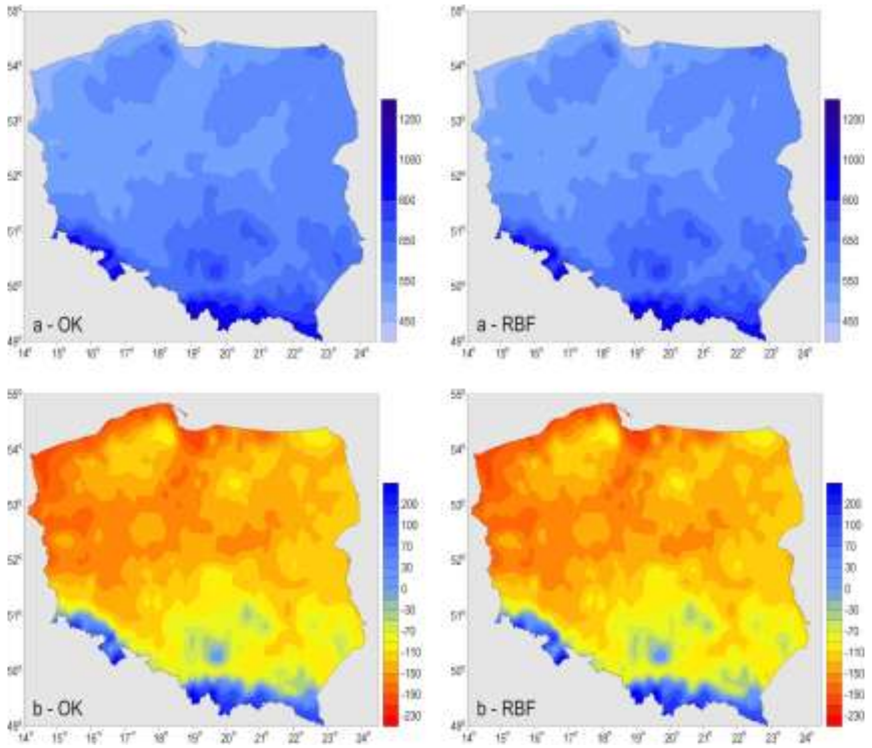

Fig. 2a. Spatial distribution of the *CWB* (mm) in Poland according to different interpolation methods: radial basis function (RBF) and ordinary kriging (OK) (simple regression model); a – annual values, b – vegetation period (April – September) values.

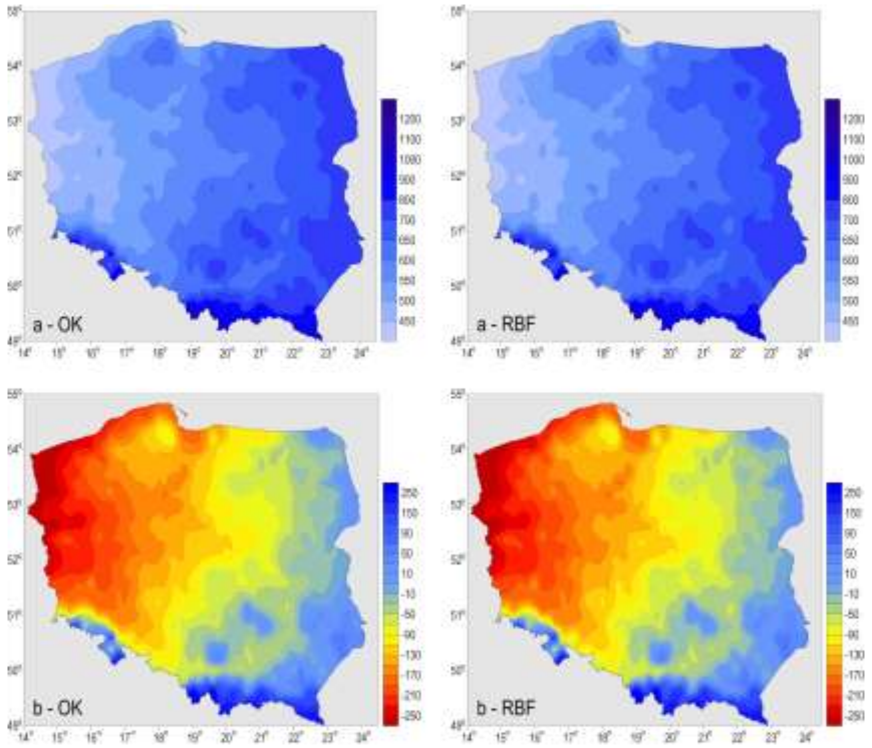

Fig. 2b. Spatial distribution of the *CWB* (mm) in Poland according to different interpolation methods: radial basis function (RBF) and ordinary kriging (OK) (multiple regression model); a – annual values, b – vegetation period (April – September) values.

Decidedly larger differences between values calculated based on field measurements and those produced by the model in question can be observed for the growing season. Using the simple regression model, errors exceed 100% of values calculated for the Jelenia Góra Basin and the Kłodzko Basin (*Fig. 3*). The multiple regression model performs the worst for coastal locations (Łeba, Kołobrzeg) and points near the eastern border of Poland – Lesko (*Fig. 3*). The uncertainty of the results obtained suggests that it is necessary to use supplemental descriptive variables.

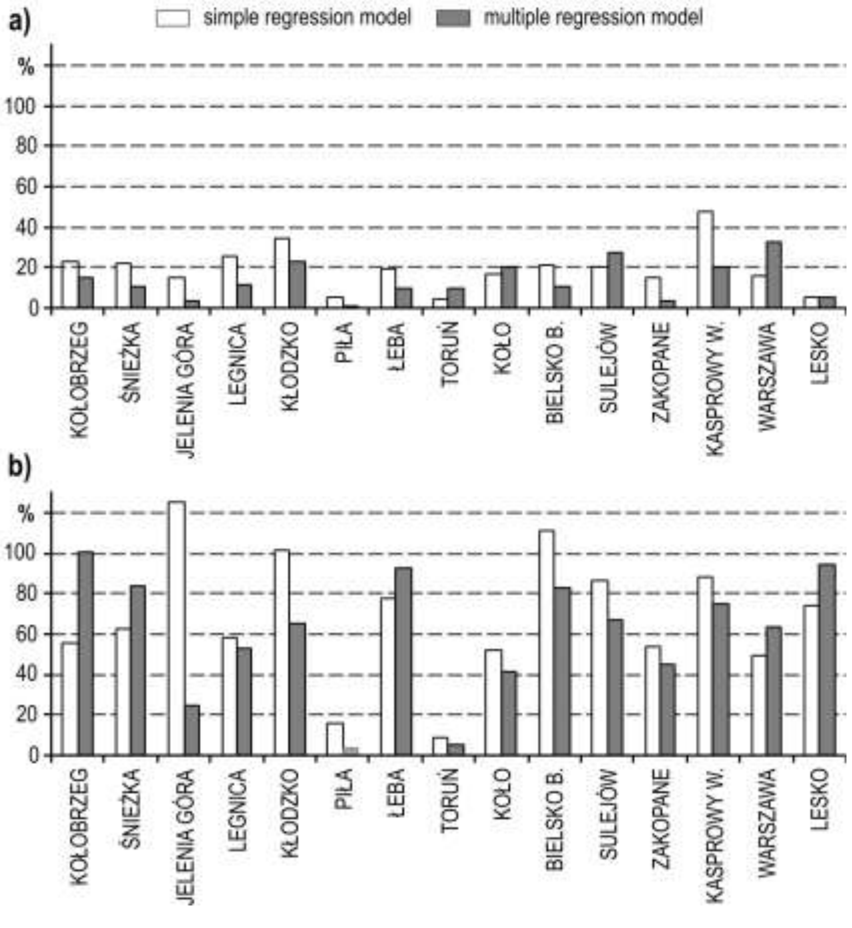

Fig. 3. Mean percent error of estimated and calculated *CWB* values for the meteorological stations used in the research study.

Component variables such as atmospheric precipitation and potential evapotranspiration make the climatic water balance strongly dependent on local conditions. Any analysis of data must take into account local relief and land cover (biological and soil factors). Elevation above sea level and geographic coordinates are not enough to perform an accurate spatial analysis of climatic water balance.

As elevation above sea level is a key component of spatial differentiation analysis of atmospheric precipitation (*Bac-Bronowicz,* 2003; *Łupikasza et al.*, 2007), the choice of descriptive variables is a key factor in spatial *CWB* analysis.

Errors may also occur as a result of poor spatial coverage provided by weather stations as well as the interpolation and mapping techniques used. Regarding evapotranspiration estimates mapping, it is usually affected by modeling errors resulting from the derivation of *ET* values (*Climatic Atlas…*, 2001). Hence, the complexity of the evapotranspiration process demands the consideration of local conditions.

The state of current understanding of microclimate differentiation, especially that in mountain areas, suggests that other geographic variables should be taken into consideration. In order to accurately describe the spatial distribution of *CWB*, it is necessary to take into account slope, aspect, land use, and soil type – all of which determine how much solar radiation is available and, consequently, the value of the air temperature (*Ustrnul* and *Czekierda*, 2005). Both solar radiation and air temperature affect the degree of evapotranspiration. Furthermore, the parameters must be calculated independently for smaller regions – especially regions characterized by specific mesoclimate conditions such as those found in coastal or mountain areas.

4. Conclusions

The spatial interpolation results presented herein, based on four different interpolation methods, prove the hypothesis that spatial differentiation analysis of the climatic water balance should take local conditions into account. The validation results are sufficient to fully assess results obtained on a national scale (Poland only), but insufficient with respect to individual geographic locations, where local differences can be quite significant.

Reducing the size of the research area appears to be a reasonable next step. A solid understanding of the causes and effects of particular component elements, such as the natural environment, on the *CWB* index should help in the process of selecting descriptive variables. Existing research suggests the use of distance from a body of water, land cover, and relief as supplemental factors. Another key factor is the selection process of the evapotranspiration (potential and/or actual) calculation method, as this appears to be the main source of possible *CWB* errors.

Given the difficult nature of the analytical process involved, the accuracy of the spatialization method is less important. The most important objectives for further research are validation of the obtained results using different evapotran-spiration formulas and the optimization and testing of spatialization techniques. A few other descriptive variables should also be considered (e.g., circulation types, air masses). Further research will be designed to focus on different temporal and spatial scales as well as the validation in other areas of Europe.

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