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Flood Frequency Analysis by an Event-based Rainfall-Runoff Model in Selected Catchments of Southern Poland

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Abstract

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The study evaluated the applicability of Event-Based Approach for Small and Ungauged Basins (EBA4SUB) for calculating annual peak flows with a specific return period (Q_T) in southern Poland. Data used in the calculations in a form of observation series of annual peak flows were derived from the Institute of Meteorology and Water Management in Warsaw and covered a multi-year period 1971–2015. The data were statistically verified for their homogeneity, significance of monotonic trends, outliers and equality of variances. Peak flows with a given return period were estimated by a statistical method of Pearson Type III distribution, and by EBA4SUB model. The analysis showed that Q_T for the investigated catchments was the most accurately matching the values derived from the statistical method when EBA4SUB model was employed. This was evidenced by the values of average relative errors that reached 34% for EBA4SUB model (with beta hyetograph). The results of the study demonstrated usefulness of EBA4SUB model for the estimation of Q_T quantiles in catchments of the upper Vistula water region.

Keywords: EBA4SUB model; mountain catchments; probable peak flows; unit hydrograph

Annual peak flows are particularly important in describing the hydrological regime of rivers. Determination of their values is necessary for a proper design of hydroengineering structures or delineating flood risk zones (Kowalik & Wałęga 2015). In engineering hydrology Q_T quantiles are estimated by direct, indirect and empirical methods. In gauged catchments, Q_T is estimated by direct methods that involve determination of probability curves identified from statistical distributions based on observation series of annual peak flow (Q_{max}) comprising at least 30 events. Indirect methods, known in hydrological analogy, are used when shorter observation series of Q_{max} are available. Then Q_T quantiles are determined based on Q_{max} values for other gauges on the same river or the gauges closing a catchment with a similar hydrological regime (McCuen & Levy 2000). When Q_T is determined for ungauged watercourses and no methods of hydrological analogy may be used, so called empirical methods are employed that include e.g. empirical formulas or rainfall-runoff models. However, it should be remembered that the estimated values of Q_T are only approximate data on the peak flow size. Moreover, the error associated with estimating Q_T quantiles by means of empirical formulas is often significant. Therefore, a recommended method for calculating Q_T in ungauged catchments is the use of rainfall-runoff models (Gądek *et al.* 2017). Among many mathematical models used in rainfall-runoff analysis, the most common are conceptual models based on the Nash cascade of linear reservoirs (Hingray *et al.* 2014), a double cascade of reservoirs (Schaefli *et al.* 2005), models based on geomorphological laws of a river network (Grimaldi *et al.* 2012), or synthetic unit hydrographs developed by Snyder (Wałęga 2016),

https://doi.org/10.17221/153/2017-SWR

SCS-UH (Syed *et al.* 2012), Clark-UH (Adib *et al.* 2011) and others.

Studies on determining Q_T with the use of rainfall-runoff models in the catchments of southern Poland were conducted by Wałęga *et al.* (2011). A paper published by Rogger *et al.* (2012) was aimed at assessing the suitability of Zemkost model for calculation of $Q_{max1\%}$ in selected catchments of the Austrian Alps. Similar studies were carried out in Italy and they resulted in developing Event-Based Approach for Small and Ungauged Basins in the form of software called EBA4SUB (Grimaldi & Petroselli 2014; Petroselli & Grimaldi 2015). This model has been fully adapted for determining runoff in ungauged catchments, is based on geographic information systems and on the optimization of the topographic information contained in the Digital Elevation Model (DEM), and uses the same input data necessary to apply the well-known rational formula.

Many rainfall-runoff models employ the Soil Conservation Service – Curve Number (SCS-CN) method for calculating the effective rainfall, and this often results in underestimation of the effective runoff parameters. Therefore, a solution that would provide information on the course of infiltration and enable more accurate assessment of the effective rainfall is sought after (Grimaldi *et al.* 2004, 2013a).

The aim of this study was to evaluate the applicability of EBA4SUB model in assessing annual peak flows with a given return period in selected catchments of southern Poland.

MATERIAL AND METHODS

The analysis included nine catchments located in southern Poland, in the water region of the upper Vistula. They belong to different physiographic units of the investigated river basin, i.e. to mountain, upland and flatland areas – Figure 1. Table 1 presents the following physiographic parameters of the investigated catchments: catchment area (A), watercourse length (L), mean watercourse slope (I), mean catchment slope (Ψ).

The aim of this study was executed based on observation series of Q_{max} for the analysed catchments and observation series of daily precipitation recorded at rainfall stations located in the investigated catchments. The observation series for Q_{max} and daily precipitation covered the multi-year period 1971–2015. The data were verified for homogeneity and independence (Kruskal-Wallis test), trend significance (Mann-Kendall test), outliers (Grubbs-Beck test) and equality of variances (Levene's test). Q_T for the observed series of Q_{max} was determined by a statistical method using Pearson type III distribution (Młyński 2016). Parameters of Pearson III type distribution were assessed by the maximum likelihood method.

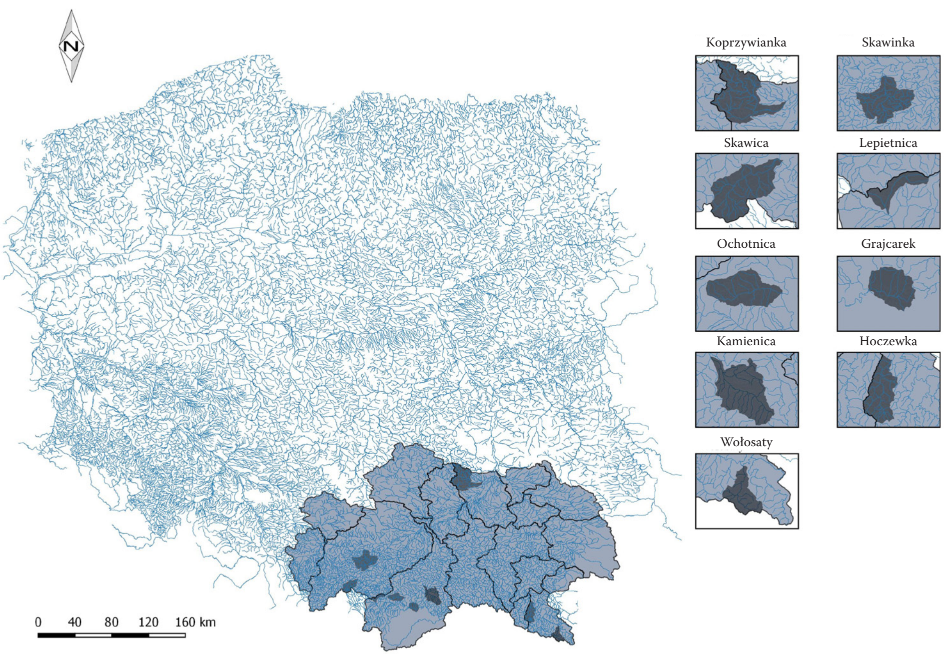

Figure 1. Localization of investigated catchments in the upper Vistula basin

https://doi.org/10.17221/153/2017-SWR

EBA4SUB model. As mentioned in the Introduction, EBA4SUB model was developed to determine the design hydrograph in uncontrolled catchments. The data required for its application include Intensity-Duration-Frequency precipitation curves, DEM of the area, and data on the catchment land use and soil properties. A novelty of EBA4SUB model is its approach to determination of effective rainfall and catchment runoff.

Precipitation hyetograph. Precipitation hyetographs in this study were determined using Chicago and DVWK methods and beta distribution. Since it was assumed that the return period of peak flow was equal to the return period of precipitation, the hyetographs were determined using maximum daily precipitation with a given return period based on the Gumbel distribution (Mejure 2011). Next, the IDF curves were created. Because it was assumed that the higher runoff from catchments is caused by rainfall having duration equal to the concentration time, in this paper assumed rainfall duration is equal to the concentration time. In order to transform point precipitation into the precipitation distributed throughout the catchment, the procedure described by Leclerc and Schaake (Leclerc & Schaake 1972) was employed:

$$\mathrm{ARF} = \frac{\mathrm{AR}}{\mathrm{PR}} = 1 - \mathrm{e}^{\left(-1.1\times t^{0.25}\right)} + \mathrm{e}^{-1.1\times t^{0.25} - 0.0259\times A} \qquad (1)$$

where:
ARF – area reduction rates (–)
AR – cumulative area precipitation (mm)
PR – cumulative point precipitation (mm)
t – precipitation duration (h)
A – catchment area (km^2)

Effective precipitation. A hyetograph of effective precipitation was determined according to the procedure proposed by Grimaldi *et al.* (2013a). It is based on the Curve Number (CN) method and Green-Ampt (GA) equation. The name of this method is Curve Number for Green-Ampt (CN4GA). In practice, the CN method is assumed as correct, which is due to the extensive experimental calibration of CN parameter. However, this method should not be used for precipitation events with sub-daily time scale (Woodward *et al.* 2010). Therefore, the proposed method comprises two steps. The first one involves estimation of total effective precipitation using the following formula (NRCS 2008):

$$P_n(t) = \begin{cases} \dfrac{(P-0.2S)^2}{P+0.8S} \text{ when } P \geq 0.2S \\ 0 \text{ when } P < 0.2S \end{cases} \qquad (2)$$

where:
$P_n(t)$ – effective precipitation (mm)
P – total precipitation (mm)
S – maximum potential catchment retention (mm)

The second step consists in determining the distribution of the total height of effective precipitation using the Green-Ampt equation (Green & Ampt 1911):

$$q_0(t) = \begin{cases} i(t) \text{ for } t < t_{\mathrm{pon}} \\ K_s\left(1 + \dfrac{\Delta\theta\Delta H}{I(t)}\right) \text{ for } t > t_{\mathrm{pon}} \end{cases} \qquad (3)$$

where
$q_{0\,(t)}$ – infiltration rate
t_{pon} – ponding time
I (t) – cumulative infiltration
K_s – saturated hydraulic conductivity
Δθ – change in soil-water content between the initial value and the field saturated soil-water content
ΔH – difference between the pressure head at the soil surface and the matrix pressure head at the moving wetting front

Table 1. Values of investigated physiographic parameters for analysed catchments

River – cross-section	*A* (km^2)	*L* (km)	*I* (‰)	Ψ (‰)
Kamienica Nawojowska – Nowy Sącz	238.0	33.0	17.3	31.0
Lepietnica – Ludźmierz	50.4	19.1	33.6	56.0
Ochotnica – Tylmanowa	108.0	24.0	43.8	81.8
Grajcarek – Szczawnica	85.5	15.0	33.1	84.0
Skawica – Skawica Dolna	146.0	22.7	48.0	75.0
Wołosaty – Stuposiany	118.2	27.8	21.0	59.8
Hoczewka – Hoczew	180.1	27.8	21.9	45.5
Skawinka – Radziszów	316.0	34.0	10.3	18.6
Koprzywianka – Koprzywnica	501.0	66.0	3.6	11.0

A – catchment area; *L* – watercourse length; *I* – mean watercourse slope; Ψ – mean catchment slope

https://doi.org/10.17221/153/2017-SWR

Equation (3) is based on the assumption that ponding time is achieved when total precipitation from the beginning of the precipitation event is equal 0.2 S. Calibration of parameters in the Eq. (3) is carried out automatically as in Grimaldi *et al.* (2013b). In practice, the second step requires only an assessment of CN parameter. Its value can be determined from the official tables of Natural Resources Conservation Service (NRCS 2008), or from similar associations between land cover characteristics and CN.

Runoff hydrograph. Runoff hydrograph is determined using a Digital Elevation Model (DEM) subjected to pre-processing analysis, and using geomorphological instantaneous unit hydrograph (IUH).

DEM pre-processing analysis is performed as follows: pits and flat areas are removed using a Physical Erosion Model for PIT removal (PEM4PIT) (Santini *et al.* 2009). The flow path is defined using an optimized flow direction algorithm, according to the method proposed by Nardi *et al.* (2008). River network is extracted using the drop analysis (Tarboton *et al.* 1991).

The chosen IUH model is based on the width function that is expressed as (Grimaldi *et al.* 2010):

$$WFIUH(t) = \frac{L_c(x)}{V_c(x)} + \frac{L_h(x)}{V_h(x)} \quad (4)$$

where:

L_c, L_h – the length of the path for channel and hillslope cell x of the DEM,

V_c, V_h – surface flow velocity for channel and hillslope cell

Parameters L_c and L_h are determined based on optimized flow direction. The values of V_c and V_h represent parameters affecting the shape of *WFIUH*. The lag time is expressed based on the basin concentration time (T_c) calculated from Giandotti's formula (Grimaldi *et al.* 2012).

After defining *WFIUH*, unit runoff hydrograph $q(t)$ is described by the following equation:

$$q(t) = \int_0^t WFIUH(t-\tau)P_n(\tau)d\tau \quad (5)$$

where:

A – catchment area (km^2)

t – precipitation duration (h)

τ – time step in precipitation duration (h)

$P_n(\tau)$ – height of effective precipitation determined by CN4GA method (mm)

RESULTS AND DISCUSSION

Statistical verification of the data on annual peak flows included checking homogeneity and independence by Kruskal-Wallis (KW) test, significance of the trend by Mann-Kendall (MK) test; outliers by Grubbs-Beck (GB) test, and homogeneity of variances by Levene's test. The study was conducted for the significance level α = 0.05. Results of the analyses are presented in Table 2.

The results of the KW test revealed significant differences in Q_{max} for the investigated periods in the catchments of the Hoczewka and Skawinka streams. The outcomes yielded by KW test for the other catchments indicated that the investigated random variables originated from the same general population. The values received from MK test confirmed that the trends of annual peak flows determined for the catchments of the Grajcarek, Wołosaty and Hoczewka streams were significant. The main factor contributing to obtaining significant results in the selected catchments is probably the course of precipitation. The water region of the upper Vistula is increasingly often affected by long streaks of extremely high precipitation that dramatically increases the river supply (Walega *et al.*

Table 2. Results of statistical analysis conducted for the investigated catchments

River	Kruskal-Wallis test		Mann-Kendall test		Grubbs-Beck test		Levene test	
	χ^2	P	Z	P	X_D	X_G	W	P
Kamienica Naw.	0.805	0.370	0.998	0.243	10.480	1143.3	0.948	0.482
Lepietnica	1.067	0.302	1.233	0.187	1.320	246.620	0.540	0.482
Ochotnica	2.281	0.131	–1.164	0.203	3.110	130.750	5.963	2.059
Grajcarek	0.003	0.953	5.674	0.000	1.991	148.814	0.598	0.480
Skawica	0.516	0.982	0.137	0.395	8.170	296.620	1.311	2.059
Wołosaty	2.626	0.105	2.397	0.023	16.064	257.864	0.442	0.480
Hoczewka	6.241	0.013	2.172	0.038	11.159	233.497	0.078	0.482
Skawinka	3.902	0.048	1.252	0.182	5.100	815.220	0.270	0.482
Koprzywianka	1.068	0.302	–0.333	0.377	2.160	218.870	0.086	0.482

χ^2 – chi square statistic; P – probability; Z– Mann-Kendall statistic; X_D – ower limit; X_G – upper limit; W – Levene statistic

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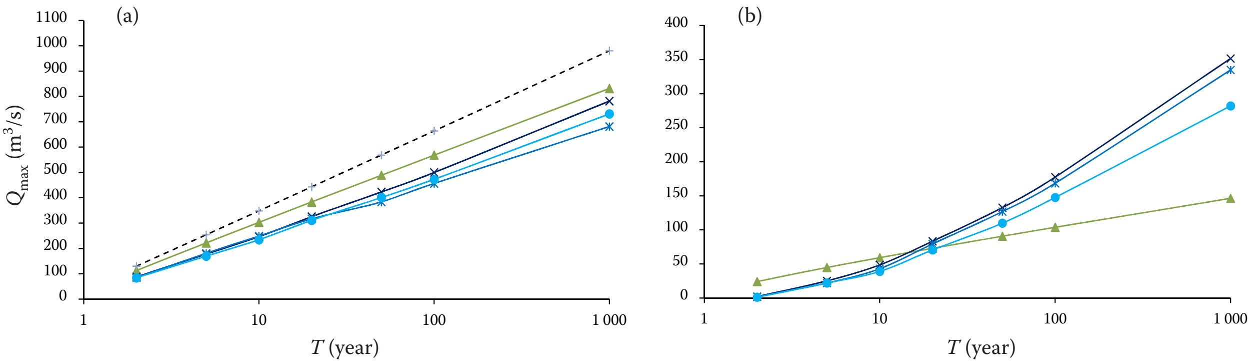

Figure 2. Annual peak flows (Q_{max}) with a given return period determined by the analysed methods for the Kamienica Nawojowska (a) and the Koprzywianka (b) streams

2016). However, stability of the hydrological regime was confirmed for the other investigated catchments. In addition, lack of outliers in the observation series of Q_{max} and homogeneity of variances in these series were indicated by Levene's and GB tests, respectively.

It must be highlighted that the catchments in which results of KW and MK tests were significant were also analysed. Yue *et al.* (2002) noted that a statistically significant trend may not be practically significant and vice versa. Sufficiently large samples will reveal any change, no matter how small, through the use of a statistical test, but this may not be of any practical help. Likewise, small samples may fail to detect a change statistically, but the degree of change might be of practical significance. Hence, these catchments were included in the analysis.

A very important element in the discharge calculation is the shape of the precipitation hyetograph especially in hypothetical flood waves and flood frequency calculations, where it is necessary to assume a specific model of precipitation distribution in time. In the Wałęga *et al.* (2012) paper the impact of the hyetograph shape on discharge values, obtained from an assumed rainfall-runoff model, was assessed. It was concluded that the hyetograph shape has a significant impact on differences in peak discharges, even at a 20% level. According to Oliveira and Stolpa (2003) constant-intensity hyetographs with duration equal to the watershed time of concentration, on the other hand, generate significantly lower peak flows. Based on the cases presented in this article, it appears that, as the watershed size (i.e., time of concentration) and curve number decrease, back-loaded hyetographs produce the highest peak flows. Accordingly, as the watershed size and curve number increase, centre-loaded hyetographs are the ones that produce the highest peak flows.

Figure 2 shows Q_T values yielded by the statistical method (PIII and EBA4SUB model) using the following hyetographs of precipitation: Chicago (1), DVWK (2) and beta (3) for the catchments with the smallest (Kamienica Nawojowska stream) and the largest (Koprzywianka stream) differences in Q_T determined from the statistical method and EBA4SUB model. Table 3 contains the values of relative errors. Figure 3 shows comparison of average relative error in QT for the investigated EBA4SUB model with respect to the statistical method.

The results of the study indicated the smallest differences in Q_T determined by the statistical method and EBA4SUB model for the Kamienica Nawojowska stream and the greatest differences for the Koprzywianka stream. The smallest average relative error of Q_T (15%) determined from EBA4SUB model was yielded by Chicago hyetograph. A comparison of

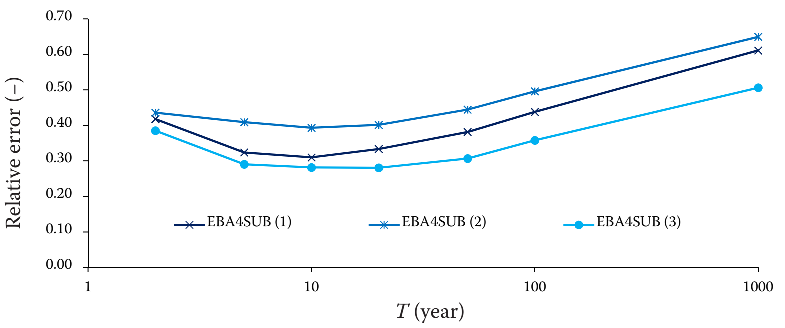

Figure 3. Comparison of average relative error in Q_T for the investigated EBA4SUB model with respect to the statistical method

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Q_T yielded by EBA4SUB model and the statistical method showed that the values were overestimated in the return period interval of 1000 to 20 years, and for the interval of 10 to 2 years they were lower than those derived by the statistical method. The smallest average relative error for EBA4SUB model (40%) was achieved for beta distribution.

In the majority of the analysed cases, the values of Q_T obtained from EBA4SUB model were most similar to the values obtained by the statistical method. Considerable differences in the results were noticed only for the flatland catchment of the Koprzywianka stream. These differences may be due to DEM preprocessing involving the removal of pits and flat areas in order to carry out further hydrological analyses. As demonstrated in Petroselli and Fernandez Alvarez (2012) and in Fernandez Alvarez *et al*. (2016), PEM4PIT application shows the best performance for mountain areas. In flatland catchments, the efficiency of this algorithm is reduced, which in turn contributes to significant disparities in determined runoff in relation to its actual values.

Table 3. Relative errors in Q_T values yielded by the statistical method and EBA4SUB model

Return period	2	5	10	20	50	100	1000
Kamienica Nawojowska – Nowy Sącz							
EBA4SUB (1)	0.22	0.20	0.19	0.15	0.13	0.12	0.06
EBA4SUB (2)	0.25	0.19	0.18	0.17	0.22	0.20	0.18
EBA4SUB (3)	0.25	0.24	0.23	0.19	0.18	0.17	0.12
Lepietnica – Ludźmierz							
EBA4SUB (1)	0.51	0.41	0.36	0.31	0.28	0.24	0.15
EBA4SUB (2)	0.53	0.37	0.33	0.26	0.25	0.25	0.21
EBA4SUB (3)	0.41	0.32	0.28	0.21	0.20	0.17	0.08
Ochotnica – Tylmanowa							
EBA4SUB (1)	0.22	0.10	0.28	0.44	0.56	0.67	0.98
EBA4SUB (2)	0.07	0.35	0.51	0.68	0.79	0.85	1.03
EBA4SUB (3)	0.24	0.07	0.20	0.33	0.43	0.52	0.73
Grajcarek – Szczawnica							
EBA4SUB (1)	0.01	0.26	0.42	0.56	0.57	0.76	1.05
EBA4SUB (2)	0.23	0.66	0.82	1.00	0.96	1.16	1.31
EBA4SUB (3)	0.07	0.31	0.42	0.56	0.54	0.68	0.91
Skawica – Skawica Dolna							
EBA4SUB (1)	0.08	0.34	0.52	0.64	0.74	0.78	0.86
EBA4SUB (2)	0.14	0.44	0.57	0.68	0.72	0.77	0.94
EBA4SUB (3)	0.06	0.17	0.23	0.44	0.51	0.60	0.80
Wołosaty – Stuposiany							
EBA4SUB (1)	0.65	0.46	0.34	0.24	0.11	0.02	0.24
EBA4SUB (2)	0.66	0.42	0.31	0.20	0.08	0.00	0.19
EBA4SUB (3)	0.63	0.44	0.36	0.23	0.10	0.02	0.22
Hoczewka – Hoczew							
EBA4SUB (1)	0.38	0.14	0.02	0.11	0.21	0.29	0.54
EBA4SUB (2)	0.40	0.16	0.04	0.07	0.17	0.22	0.40
EBA4SUB (3)	0.26	0.08	0.05	0.16	0.25	0.33	0.52
Skawinka – Radziszów							
EBA4SUB (1)	0.77	0.56	0.49	0.43	0.38	0.33	0.21
EBA4SUB (2)	0.72	0.58	0.52	0.46	0.42	0.38	0.29
EBA4SUB (3)	0.59	0.48	0.42	0.38	0.34	0.32	0.24
Koprzywianka – Koprzywnica							
EBA4SUB (1)	0.91	0.44	0.18	0.14	0.46	0.71	1.40
EBA4SUB (2)	0.92	0.51	0.27	0.09	0.40	0.62	1.29
EBA4SUB (3)	0.95	0.51	0.34	0.03	0.21	0.42	0.93

CONCLUSIONS

The study evaluated the applicability of EBA4SUB model in assessing annual peak flows with a given return period in selected catchments of southern Poland. Considering the obtained results, the EBA4SUB model was found suitable for calculating annual peak flows with a given return period in catchments. Our analysis allowed us to recommend this model to determine Q_T using beta hyetograph in the catchments of southern Poland and also in the catchments of neighbouring countries with similar physiographic and weather parameters. This was evidenced by the results of the calculations, as the most accurate Q_T values were obtained from EBA4SUB model and beta hyetograph. However, further studies on the optimization of EBA4SUB model parameters are recommended to ensure the most accurate determination of runoff in the catchments of southern Poland and neighbouring countries.

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