Regional relationships between basin size and runoff characteristics

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ABSTRACT The effect of basin size on runoff characteristics is investigated. The maximum observed floodflow, the maximum annual constant loss, the lag time and the unitgraph peak for a certain storm duration of basins in the western and northwestern regions of Greece are increasing power functions of the basin size. These functions explain significantly the variation in the runoff characteristics. For both regions single relationships are derived for the latter two characteristics, whereas for the two former ones they vary regionally in accordance to the climatic conditions. Thus, care is needed in transferring such relationships outside the location of their derivation; besides, the transferability of the values of their parameters is doubtful. The derivation of the relationships in the specific area of interest is thus suggested. The regional relationships are used in predicting accurately design floodflows, annual runoff yields and unitgraphs of various storm durations for ungauged basins in the regions studied, needed for the hydrological design of water resources development systems.

Relations régionales entre la surface du bassin et les caractéristiques de l'écoulement

RESUME On étudié l'influence de la surface du bassin versant sur les caractéristiques de l'écoulement. Le débit de la crue maximale observée, la constante de perte maximale annuelle, le temps de réponse et la pointe de l'hydrogramme unitaire pour une durée donnée de l'averse, pour les bassins versants dans les régions ouest et nord-ouest de la Grèce sont des fonctions puissance croissante de la surface du bassin. Ces fonctions expliquent de façon significative les variations des caractéristiques de l'écoulement. Pour chacune de ces deux régions des relations uniques sont établies pour deux dernières caractéristiques, tandis que pour les deux premières, elles sont d'une région à l'autre en accord avec les conditions climatiques. Ainsi, il est nécessaire de rester vigilant pour transférer de telles relations en dehors des régions pour lesquelles elles ont été établies; en outre, la possibilité de transférer leurs paramètres est douteuse. On propose donc que cette relation soit utilisée dans la zone intéressée par les
INTRODUCTION

The transfer of hydrological data, parameters or relationships obtained from one basin, e.g. from a representative basin, to others, or their estimation for ungauged basins, has obvious practical importance. Several research studies are available in the literature dealing with this subject and especially with the transferability of runoff or of related process characteristics and relationships and with the estimation of the latter by using geomorphological characteristics of the basin (USGS, 1967; Flint, 1974; Vorst & Bell, 1977; Baron et al., 1980; Cordery et al., 1981; Mimikou, 1982). Current knowledge of hydrological and geomorphological processes and the results of published studies indicate that basin size, or some of its related functions like stream length and slope, can be expected to influence runoff significantly in a number of direct and indirect ways. Basin size has been often used in estimating and predicting runoff (Matthai, 1969; Crippen, 1982; Pilgrim et al., 1982; Mimikou, 1984).

In this paper the effect of basin size on runoff characteristics, more specifically on the maximum observed floodflow, the maximum annual constant loss, the lag time and the unitgraph peak for a certain storm duration of river basins in Greece, is investigated. The basin studies range in size and cover a significant part of the western and northwestern regions of Greece. Regional relationships are developed which explain significantly the variation in the runoff characteristics in terms of the basin size. The form of the relationships and their accuracy are discussed and explained. Their regional variation in accordance to the climatic conditions and to other causative factors, which in addition to the basin size influence runoff, is investigated. The transferability of the values of their parameters from place to place is discussed. Conclusions are drawn for the transferability of the relationships and for their use in accurately predicting design floodflows, annual runoff yields and unitgraphs of various storm duration for ungauged basins in the regions studied. These are needed for the hydrological design of various water resources development systems.

DATA USED

For several basins in Greece, the effect of basin size on runoff characteristics is investigated by means of a regressional analysis between the size (in km$^2$) and the maximum observed floodflow (instantaneous) $Q_p$ (in m$^3$s$^{-1}$), the maximum annual constant loss CL (in mm), the lag time $t_L$ (in h) and the unitgraph peak $q_p$ (in m$^3$s$^{-1}$) for a certain storm duration. The basins range widely in size and
cover a significant part of the western and northwestern regions of Greece (Table 1). The runoff of the basins is measured at their outlets where flow measuring stations are located equipped with staff gauge recorders and flow measuring devices operated since 1962 and belonging to the Greek Power Corporation. The general location of the basins and of their flow measuring stations is shown in Fig. 1. Eleven of the basins given in Table 1 with their sizes $A$ (in km$^2$) and their runoff characteristics have been used in the calibration of the regional relationships developed. Two basins, given with their characteristics in Table 2, have been additionally used in verifying the efficiency and the accuracy of the relationships developed for predicting runoff characteristics. In Tables 1 and 2, the region to which each river basin belongs is also given. The regions are distinguished according to their physiographic,
Table 1  Basin sizes and runoff characteristics

<table>
<thead>
<tr>
<th>River</th>
<th>Measuring station</th>
<th>Basin size A (km²)</th>
<th>Floodflow Qp (m³/s)</th>
<th>Max. annual constant loss CL (mm)</th>
<th>Lag time tL (h)</th>
<th>Unitgraph peak qp (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Western region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acheloos</td>
<td>Avlaki</td>
<td>1349</td>
<td>2148</td>
<td>500</td>
<td>8.0</td>
<td>280</td>
</tr>
<tr>
<td>Acheloos</td>
<td>Kremasta</td>
<td>3570</td>
<td>4400</td>
<td>972</td>
<td>15.0</td>
<td>400</td>
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<td>Tsimovo</td>
<td>640</td>
<td>896</td>
<td>370</td>
<td>7.0</td>
<td>200</td>
</tr>
<tr>
<td>Arachthos</td>
<td>Plaka</td>
<td>970</td>
<td>1360</td>
<td>420</td>
<td>7.5</td>
<td>230</td>
</tr>
<tr>
<td>Arachthos</td>
<td>Arta</td>
<td>1855</td>
<td>2100</td>
<td>820</td>
<td>8.5</td>
<td>440</td>
</tr>
<tr>
<td><strong>Northwestern region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kalamas</td>
<td>Vrossina</td>
<td>1031</td>
<td>859</td>
<td>300</td>
<td>8.5</td>
<td>170</td>
</tr>
<tr>
<td>Aoos</td>
<td>Vovoussa</td>
<td>202</td>
<td>380</td>
<td>200</td>
<td>4.0</td>
<td>71</td>
</tr>
<tr>
<td>Aoos</td>
<td>Konitsa</td>
<td>665</td>
<td>700</td>
<td>280</td>
<td>6.5</td>
<td>190</td>
</tr>
<tr>
<td>Aliakmon</td>
<td>Siatista</td>
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<td>1358</td>
<td>520</td>
<td>11.0</td>
<td>420</td>
</tr>
<tr>
<td>Aliakmon</td>
<td>Iliarion</td>
<td>5005</td>
<td>2100</td>
<td>600</td>
<td>16.0</td>
<td>780</td>
</tr>
<tr>
<td>Venetikos</td>
<td>Venetikos</td>
<td>818</td>
<td>950</td>
<td>330</td>
<td>7.0</td>
<td>210</td>
</tr>
</tbody>
</table>

Table 2  Prediction of runoff characteristics

<table>
<thead>
<tr>
<th>River</th>
<th>Measuring station</th>
<th>Basin size A (km²)</th>
<th>Floodflow Qp (m³/s)</th>
<th>Max. annual constant loss CL (mm)</th>
<th>Lag time tL (h)</th>
<th>Unitgraph peak qp (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Western region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kalaritikos</td>
<td>Gogo bridge</td>
<td>203</td>
<td>420(395)*</td>
<td>205(191)*</td>
<td>4.0(4.0)*</td>
<td>84(79)*</td>
</tr>
<tr>
<td><strong>Northwestern region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aliakmon</td>
<td>Prodromos</td>
<td>6075</td>
<td>2180(2242)*</td>
<td>680(644)*</td>
<td>17.0(16.4)*</td>
<td>900(758)*</td>
</tr>
</tbody>
</table>

*The predicted values are given in parentheses.

hydrological and climatological features.

The floodflows, Qp, are the maximum observed peak discharges at the flow measuring stations during their period of operation. Investigations have shown that these peak discharges are actually the largest events to have occurred during the past 29 years, namely since 1954 (Mimikou, 1984). No reliable earlier historical flood information could be found. Thus, the return period which could now be assigned to the floodflows, Qp, of the analysis by using a plotting position equal to the number of observation years plus one (Gumbel, 1958), is 30 years. As the years pass, this return period increases and the maximum observed floodflows, Qp, and thus their regional relationships presented in the following are eventually modified whenever new floodflow observations exceed the analysed flood data. The majority of the floodflows, Qp, have not been measured directly due to equipment inefficiency during very high discharges but they have been estimated from well established extensions of stage-discharge rating curves of the stations by using the maximum observed water level readings from the stage recorders. Instead of the maximum observed peak discharges, Qp, floodflows of a selected frequency could be considered, e.g. the 20-year or the 30-year flood. This would require frequency analyses of each station, a procedure which would involve an assumption of the form of the suitable frequency distribution. The latter may vary from station to station and need to be modified with the collection of further data. This would result in changing the estimated floodflow values for all stations even in the cases where the corresponding
maximum observed floodflows, $Q_p$, are not exceeded. The above discussion clearly shows that the maximum observed floodflows are preferable, since their estimation procedure is free of assumptions, sampling errors, etc., and besides they reliably represent the maximum flood experience of the area.

The maximum annual constant loss, $C_L$, has been determined for each basin as the difference between the line of equal annual areal rainfall and runoff (with no loss) and the actual rainfall–runoff curve at high rainfall values, where it becomes approximately parallel to the line of equality (Pilgrim et al., 1982). The annual areal rainfall and runoff depths in mm have been estimated for each basin by using annual point rainfalls (including snowfall) according to the Thiessen polygon method and the corresponding annual runoff volumes from the outlet station divided by the drainage area, respectively.

The lag time, $t_L$, is the time difference between the centroid of the rainfall and the peak of runoff (Linsley et al., 1975). The lag time, $t_L$, and the unitgraph peak, $q_p$, have been estimated at the outlets of the basins from unitgraphs produced by uniform net 10-mm rainfall depths of a common duration equal to 6 h for all basins. The common storm duration was decided in order to avoid the effect of a varying storm duration on the variation of the $t_L$ and $q_p$ values from basin to basin (Linsley et al., 1975), which would cause problems (significant scatter of data, etc.) in explaining the variation in the variables in terms of the basin size. The 6-h unitgraph for the estimation of the $t_L$ and the $q_p$ values of each basin has been derived from observed flood hydrographs and complex areal storms of varying lengths discretized in 6-h intervals according to the well known multi-period technique described in the literature (Linsley et al., 1975). The 6-h duration has been found to be a common convenient storm time discretization, meeting in all cases the requirements for a reliable unitgraph derivation (rainfall spatial and temporal uniformity, etc.).

**EFFECT OF BASIN SIZE ON RUNOFF CHARACTERISTICS. RUNOFF PREDICTION**

The relative scarcity of stations for measuring runoff in the western and northwestern regions of Greece in connection with the intensive development of the water potential of the area, especially for hydroelectric energy production, creates the necessity for developing regional methods for transferring runoff information from gauged basins to ungauged ones by using basin geomorphological characteristics. The latter can be easily obtained from a map. For this purpose regional relationships between basin size and runoff characteristics were derived in the area.

**Regional analysis**

Each of the four runoff characteristics previously defined and given in Table 1 is plotted against the basin size, $A$. The plottings for the floodflow, $Q_p$, (Mimikou, 1984) and the maximum annual constant loss, $C_L$, are given together on a loglog scale in Fig. 2. The plotted points for each of the two variables are clearly classified into two
groups of points which are linearly associated. The upper groups include the points corresponding to the Arachthos and the Acheloos river basins of the western region and the lower groups the points corresponding to the Kalamas, the Aoos, the Aliakmon and the Venetikos river basins of the northwestern region. This regional separation is in accordance with the climatic conditions and the hydrological experience from the area, which lead to higher floodflows and higher annual losses for the same drainage area in the western than in the northwestern region of Greece. This is because of the climatological and the physiographical differences of the two regions, since the western region of Greece receives much higher precipitation depths than the northwestern region. It appears from Fig.2 that for decreasing basin sizes the two groups of points for both runoff characteristics approach each other. Thus one can reasonably assume that for relatively small basin sizes, i.e. for \( A < 300 \text{ km}^2 \), the maximum floodflow rates and the annual constant losses per unit area of the two regions are equalized. Inspecting Fig.2 one can easily see that the regional curves of the northwestern region appear to be more appropriate than those of the western region for representing the single relationships between
basin size and each of the two runoff characteristics for small basins. This assumption is verified in the following. The least squares lines drawn through the groups of points as shown in Fig.2 are characterized by very high coefficients of determination, $r^2$, and have the following analytical expression in a power functional form:

\[
\begin{align*}
\text{W region:} & \quad Q_p = 2.948A^{0.892}, \quad r^2 = 0.96 \\
\text{NW region:} & \quad Q_p = 26.140A^{0.511}, \quad r^2 = 0.98 \\
\text{W region:} & \quad CL = 8.362A^{0.575}, \quad r^2 = 0.98 \\
\text{NW region:} & \quad CL = 28.714A^{0.357}, \quad r^2 = 0.97
\end{align*}
\]

Thus the maximum observed floodflow and the maximum annual constant loss are regionally varying and increasing power functions of the basin size. The main reasons for the increase seem to be the runoff volume for the floodflows and the channel transmission losses for the annual losses, which increase with increasing basin size. The regional variation is due to the existence of other causative factors, like the precipitation and generally the climatological and physiographic characteristics of the basins, which influence the $Q_p$ and $CL$ values in addition to the basin size and which vary from region to region. Thus care is needed in transferring such relationships outside the immediate range and location of their derivation. Pilgrim et al. (1982), in reviewing the effect of basin size on runoff relationships, came to a similar conclusion. On the other hand, the loglog plottings for the lag time, $t_L$, and the unitgraph peak, $q_p$, in Fig.3 clearly show that a single linear relationship between each of them and the basin size is possible for both regions. This is due to the fact that the influence of the regionally varying rainfall characteristics on both variables has been removed, since the variables refer to standard net unit rainfall depths of common duration for both regions. The least squares curves drawn for both variables in Fig.3 are characterized by high coefficients of determination, $r^2$, and have the following analytical expressions in a power functional form:

\[
\begin{align*}
Q_p &= 0.430A^{0.418}, \quad r^2 = 0.95 \\
q_p &= 2.270A^{0.667}, \quad r^2 = 0.92
\end{align*}
\]

Thus the lag time and the unitgraph peak for a certain storm duration are increasing power functions of the basin size, a conclusion which has been drawn in many different cases by others as well. The majority of the work on relating runoff response to geomorphological characteristics considers the mainstream length and slope (Linsley et al., 1975; Pilgrim et al., 1982), which are directly related (as power functions) to the basin size (Leopold et al., 1964; Mueller, 1973; Flint, 1974). The considerably wide variety of the parameter values of regional relationships of the type developed herein derived in different places in the world (Linsley et al., 1975; Crippen, 1982; Pilgrim et al., 1982) indicates
that transfer of these parameter values from place to place is of doubtful validity. Such regional relationships should be derived in the specific area of interest.

The scatter of points around the curves drawn in Figs 2 and 3 is mainly due to data errors, such as the errors in the measurement of basin sizes from the map and the errors in estimating the analysed runoff characteristics, i.e. errors in the extrapolations of stage-discharge rating curves, in the Thiessen polygon method, in the derivation of the unitgraphs etc. The considerably high values of the coefficient of determination, \( r^2 \), for equations (1)-(6), which is a quantitative measure of the scatter of points, indicate that for all derived relationships the scatter of data is not significant and that the variation in the analysed runoff characteristics is explained significantly by equations (1)-(6) in terms of the basin size.

Fig. 3 Effect of basin size on the lag time and the unitgraph peak.
Runoff prediction: engineering applications

Equations (1)-(6) can be used in predicting extreme flood events, maximum annual constant losses and unit runoff response characteristics for ungauged basins in the western and northwestern regions of Greece by using only the basin size. More specifically, equations (1) and (2) can give evidence as to the flood magnitude to be expected from ungauged basins with a return period at least equal to the return period of the analysed data (Mimikou, 1984). Therefore they can be used in specific engineering applications, such as in the hydrological design of safety structures built for a relatively short-term flood protection, e.g. in the design of diversion works at ungauged river sites, where a dam is to be built and the prediction of a diversion design flood is needed, etc. Equations (3) and (4) can be used in estimating the maximum annual constant loss of ungauged basins, which in turn can be used in obtaining annual runoff yield estimates from annual areal rainfalls (the rainfall gauge and recorder stations network covers adequately the whole area studied). For example, the subtraction of the loss from the average annual areal rainfall gives a reliable estimate of the average annual runoff yield of the basin, which is valuable information used in the hydrological design of reservoirs and of other water resources development systems. Finally, equations (5) and (6) predict the lag time and the peak of a 6-h unitgraph at the outlet of an ungauged basin. By using the unitgraph volume \((10 \text{ mm} \times A \text{ km}^2 \times 10^3)\) in \(\text{m}^3\) and one of the unitgraph time distributions available in the literature, e.g. the Soil Conservation Service or Snyder's distribution (Linsley et al., 1975) or even a suitable geometrical scheme (triangle, trapezoid), one can easily estimate the 6-h unitgraph of the basin. Unitgraphs of any other time period required in design can be obtained from the 6-h unitgraphs (Snyder, 1938; Linsley et al., 1975).

The efficiency and accuracy of equations (1)-(6) for predicting runoff characteristics is verified by using data from two other basins, which have not been used in the calibration of the relationships. These are the Aliakmon river basin at the Prodromos station with a drainage area equal to 6075 km\(^2\) in northwestern Greece and the Kalaritikos river (a tributary of the Aracthos river) basin at the Gogo bridge station in western Greece with a drainage area equal to 203 km\(^2\). As previously explained, for basin sizes less than 300 km\(^2\) the regional relationships between basin size on the one hand and floodflows, \(Q_p\), and losses, \(CL\), as well on the other, degenerate to single relationships for both regions, which are better expressed by the curves developed for the northwestern than for the western region. Thus, the \(Q_p\) and \(CL\) values of the basin at the Gogo bridge station are estimated by using equations (2) and (4) instead of the regionally appropriate equations (1) and (3) respectively. The predicted \(Q_p\), \(CL\), \(t_L\) and \(q_p\) values for these basins are given in Table 2 in parentheses along with the actual values of the runoff characteristics, as estimated at the outlet measuring stations of the basins. Defining the prediction error, \(\varepsilon\), as:

\[
\varepsilon = \left| x - \hat{x} \right| x^{-1} \% \quad (7)
\]
with \( x \) the actual and \( \hat{x} \) the predicted value of each runoff characteristic, one can estimate from Table 2 that the prediction error for all characteristics ranges in the average between 2% and 10%. Therefore, the derived relationships can be used in predicting accurately design floodflows, annual runoff yields and unitgraphs of various storm durations for ungauged basins in the regions studied that may be needed for the hydrological design of various water resources development systems.

CONCLUSIONS

The conclusions drawn from this research are the following:

(a) The maximum observed floodflow, the maximum annual constant loss, the lag time and the unitgraph peak for a certain storm duration for basins in the western and northwestern regions of Greece are increasing power functions of basin size. These functions explain significantly the variation in the analysed runoff characteristics. For both regions single relationships are derived for the latter two characteristics, whereas for the two former ones they vary regionally in accordance to the climatic conditions.

(b) Care is needed in transferring regional relationships, like the ones developed in the study, outside the immediate range and location of their derivation since they may be regionally varying; besides, the transferability of their parameter values is doubtful. The derivation of such relationships in the specific area of interest is thus suggested.

(c) The derived regional relationships can be used in predicting accurately design floodflows, annual runoff yields and unitgraphs of various storm durations for ungauged basins in the regions studied, needed for the hydrological design of various water resources development systems.

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REFERENCES


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