$$I_p = \frac{\Delta R_P}{\Delta R} \times 100 \tag{12.16}$$

$$I_{PET} = \frac{\Delta R_{PET}}{\Delta R} \times 100 \tag{12.17}$$

$$I_n = \frac{\Delta R_n}{\Delta R} \times 100 \tag{12.18}$$

12.5 RESULTS

12.5.1 Application of the Budyko Curve

The Budyko curve is developed for the study basins by using Fu's equation (Equation (12.3)). The Budyko curve describing four basins with various climatic and geographic variability being presented in Fig. 12.5. Fig. 12.5 (a) is for a basin in New York State with humid continental climate conditions. Fig. 12.5 (b) is for a basin located in Florida with tropical climate conditions. Fig. 12.5 (c) is for a basin located in New Mexico with desert climate conditions. Figure 12.5 (d) is the Budyko curve for a basin in Washington State having an alpine climate. As seen in Fig. 12.5, the value of '*w*' can vary for different basins depending on physical and climate characteristics.

Figure 12.6 shows optimal '*w*' values for all basins in this study. While the minimum value of '*w*' is 1.05 (USGSID: 12134500), the maximum value of '*w*' is shown in West Virginia (USGSID: 03182500). Figure 12.6 also shows that the optimal '*w*' value has a spatial pattern. For example, the western U.S. has a relatively small magnitude of '*w*' values whereas stations near Kansas, Iowa and Missouri show higher values for '*w*'.

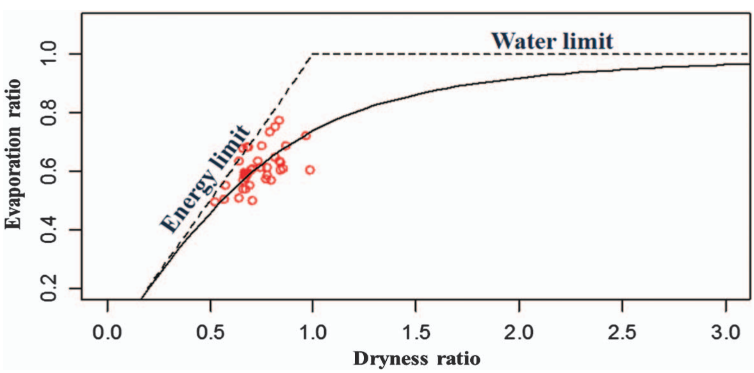

Figure 12.4. Example of the Budyko curve

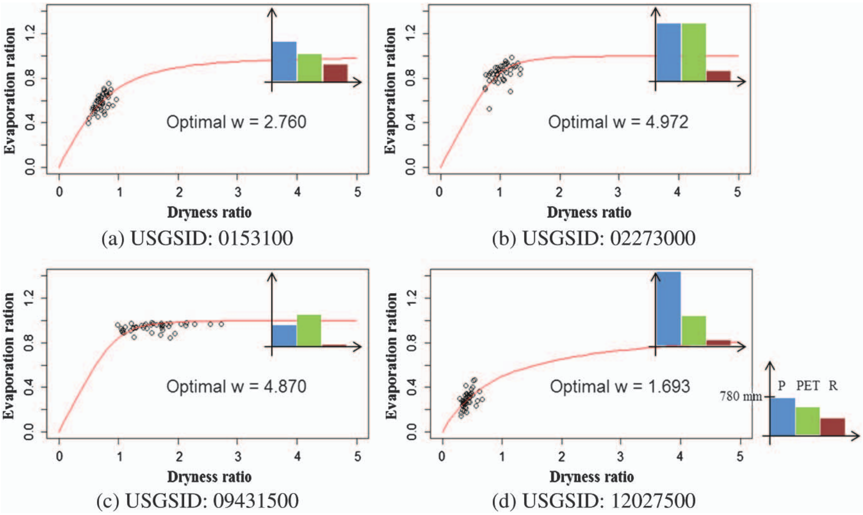

Figure 12.5. Budyko curves for four basins under different climate conditions. The line is estimated by Fu's equation. In the histogram, the first column represents the value of precipitation. The second and the third columns represent potential evapotranspiration and streamflow, respectively

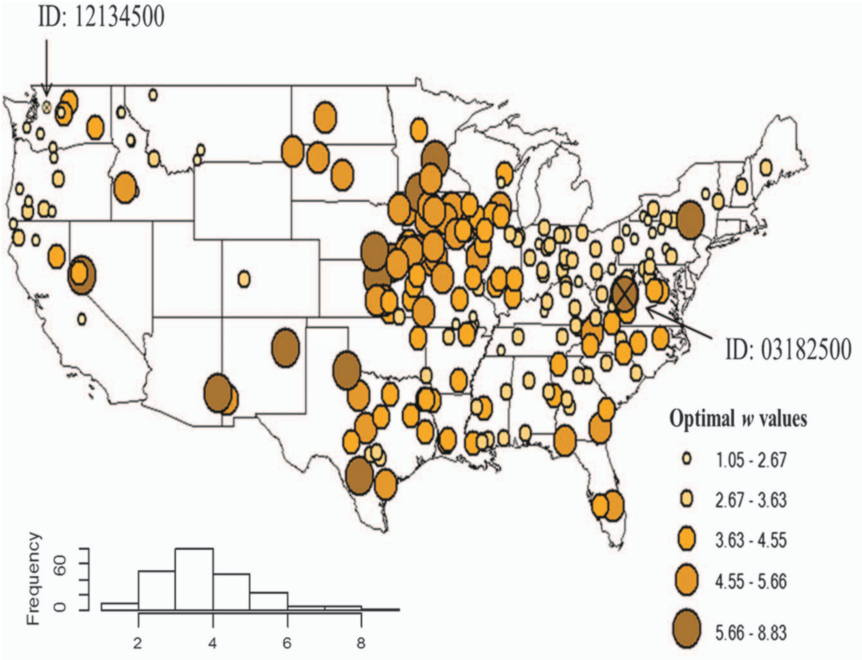

Figure 12.6. Optimal values of the w parameter in Fu's equation. Two basins (12134500 and 03182500) are marked

12.5.2 Incorporating Basin Characteristics to Get the W Parameter

It is hypothesized that the spatial pattern observed in Fig. 12.6 can be related to basin characteristics. To test this hypothesis, five basin characteristics (see Table 12.1)–saturated hydraulic conductivity, normalized difference vegetation index, basin area, basin slope, and stream length–are used in this study. Figure 12.7

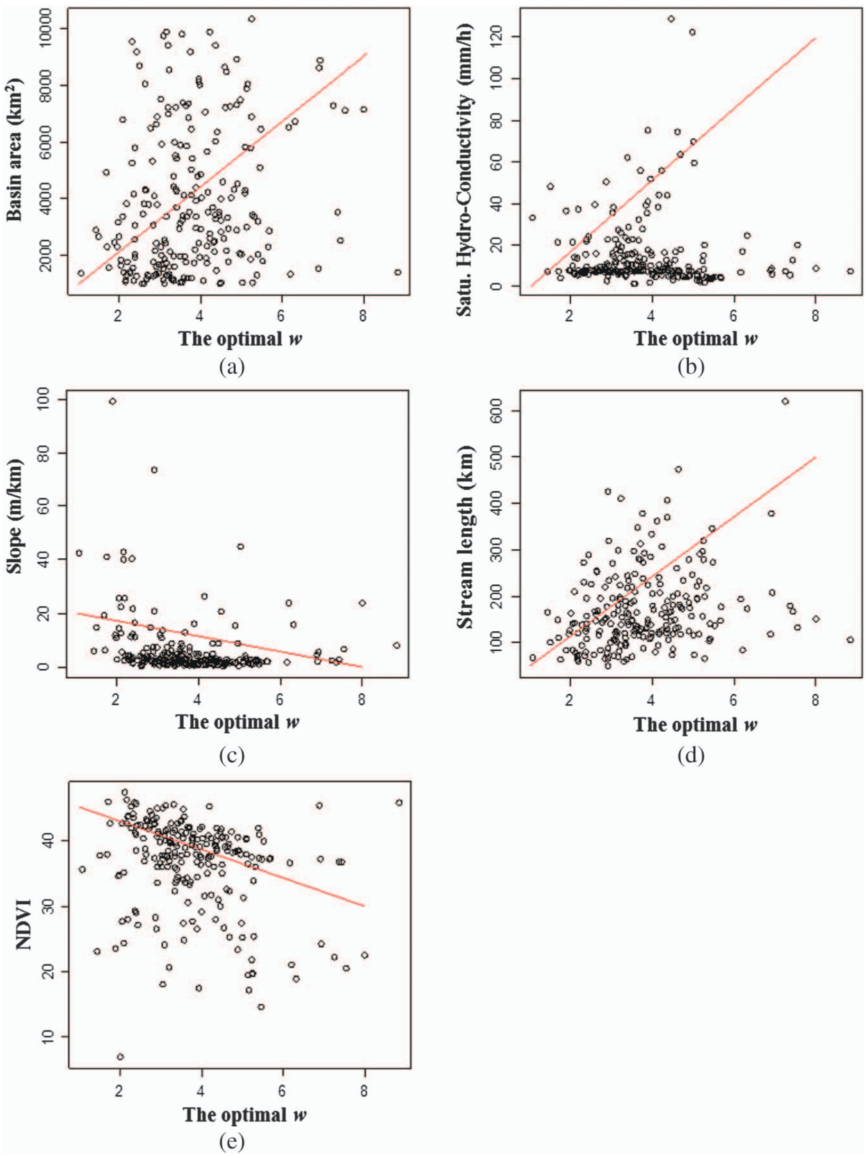

Figure 12.7. The relationship between basin characteristics and optimal w values

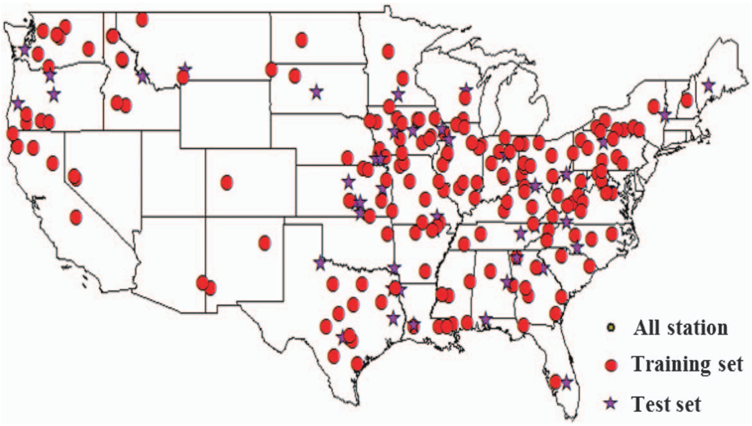

Figure 12.8. Examples of basins for the training and test sets

shows the relationship between the optimal w values and the selected basin characteristics. A multiple regression approach with a stepwise model selection method is used to determine a quantitative relationship between the optimal w values and the basin characteristics. A log transformation method is adopted to bring non-normally distributed variables into a normal distribution.

All data are split into two sets (Fig. 12.8)–a training set with 175 stations and a test set with 50 stations. Using the training set, coefficients for a multiple regression model are first estimated to determine 'w' from basin characteristics. Three variables–vegetation coverage, basin slope, and stream length–are then chosen for estimating the w parameter in Equation (12.3) based on the results of the stepwise regression.

The final expression for w is given in Equation 12.19.

$$w = 1.2170 \times M^{-0.0707} \times S^{-0.0906} \times \exp(0.0497\,L) \qquad (12.19)$$

where M is the vegetation coverage, S is the basin slope, and L is the stream length (km). Long-term (50 years) average evaporation is calculated for 50 test stations by using equation (12.3) and equation (12.19). The results calculated by equation (12.3) are considered as actual evaporation whereas the results derived from equation (12.19) are regarded as estimated evaporation. The comparison is shown in Figure 12.9.

The results are quite remarkable based on $R^2 = 0.922$. This process is repeated 1000 times by selecting 50 random stations. Each of the 50 test stations can be classified into four groups. The first group is for stations whose optimal w values are less than 2.5. The second group is defined as stations whose optimal w values are from 2.5 to 4.0. The third group is for stations which have optimal w values between 4.0 and 5.5. The last group designates stations whose optimal w values are more than 5.5. Table 12.2 shows the mean R^2 based on these four defined groups whereas Figure 12.10 shows the box plot of the R^2 values using the 1000 trials.

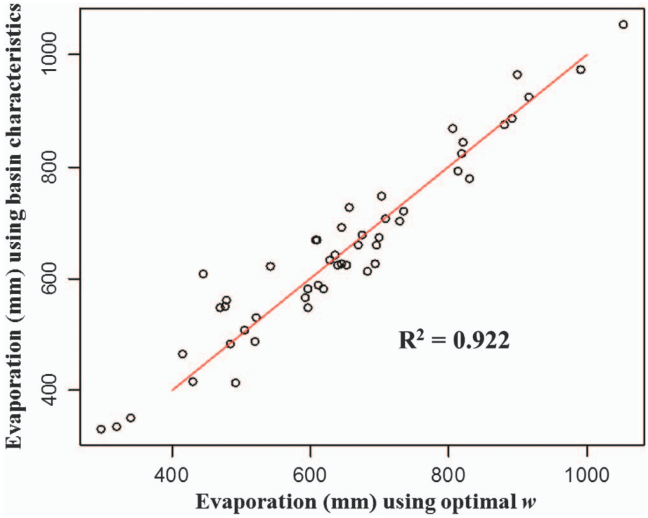

Figure 12.9. Comparison of long-term average annual evaporation estimated by optimal w values and the estimated w values using basin characteristics

Table 12.2. Mean R^2 corresponding to classifications

Classifications	*Description*	*Mean R^2*
Whole	*All w*	0.894
Group 1	$w < 2.50$	0.766
Group 2	$2.5 < w < 4.0$	0.958
Group 3	$4.0 < w < 5.5$	0.975
Group 4	$5.5 < w$	0.971

Results in Figure 12.10 show that estimation of the optimal *w* value that is greater than 2.5 is relatively more accurate than optimal values which are less than 2.5. One can conclude that basin characteristics may have a greater effect on the hydrology variables in those basins having a relatively higher value of *w*.

12.5.3 Contribution Analysis Using the Budyko Curve

The value of the parameter *n* (Equation 12.4) is estimated for each basin for two different periods: 1950–1975 and 1976–1999. The average value of '*n*' for the first period is 2.99 but is 3.07 for the second period. During the two periods, the average value of the '*n*' parameter is increased by a value of 0.08. Figure 12.11 illustrates the difference in the parameter '*n*' during the two defined periods. While the values of the parameter '*n*' are increased in many basins in the western CONUS, the values of the parameter '*n*' are consistently decreased in many basins near the Midwest area of the CONUS. Agricultural expansion in the Midwest, caused by increased

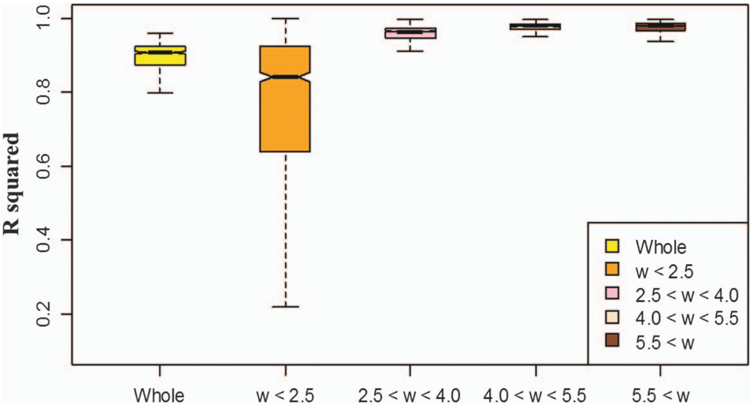

Figure 12.10. Box plot of R^2 for test sets

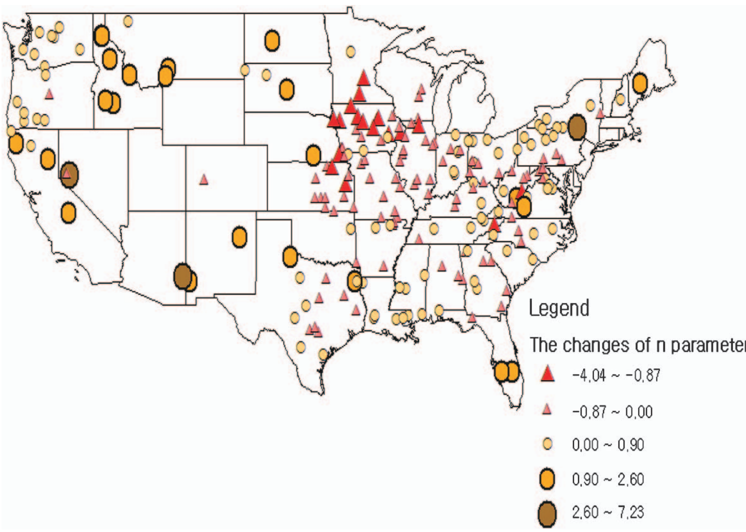

Figure 12.11. Differences in the parameter 'n' between the two defined periods

acreage of corn or soybeans, may lead to a decrease in the forested area. This change is reflected in the decrease in values of the parameter '*n*'.

Equations (12.13)–(12.15) are used to compute changes in runoff between the two defined periods based on three contributions (precipitation, potential evapotranspiration and basin characteristics change). The sum of the changes due to these three contributions should theoretically be the same as the total change in observed runoff. Figure 12.12 shows a comparison between modeled and observed streamflow changes. Here, modeled streamflow change is defined as the sum of the changes of the three contributions. In the positive changes (Equation 12.11 > 0), the results of modeled streamflow change are slightly greater than the results of

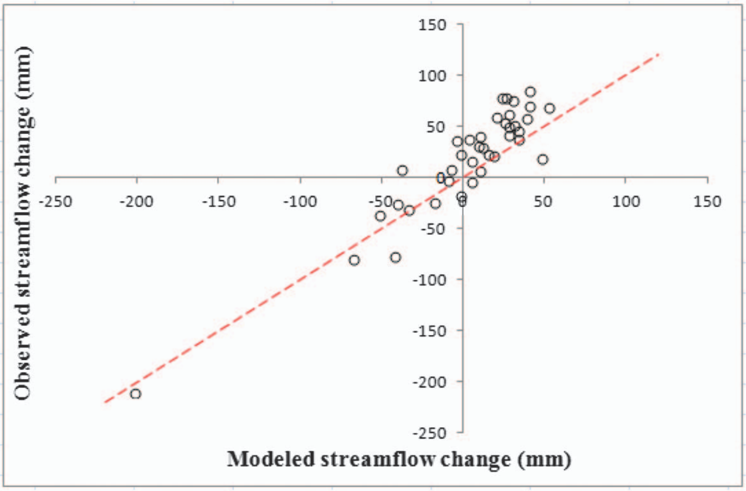

Figure 12.12. Comparison between modeled and observed streamflow changes (mm)

observed streamflow change. However, the results for most of the study basins are quite consistent.

Using the results of the three contributions, relative impacts can be calculated based on Equations (12.16)–(12.18). Figure 12.13 illustrates the results of the relative impact in 225 study basins based on these three contributions. The impacts of PET are less in most basins than the impacts of the other contributions. On the other hand, change in basin characteristics makes the largest contribution. The average contributions of the three impacts (precipitation, pet, and basin characteristics change) are 24.69%, −3.56% and 78.87%, respectively. In other words, total climate variability is 21.13% (24.69%–3.56%) whereas the impact of change in basin characteristics is 78.87%. This indicates that anthropogenic impact causes much more important changes in streamflow than does the impact of climate variability.

12.6 SUMMARY

In this study, the impact of basin characteristics and their contribution to changes in streamflow are investigated. The Budyko curve, a widely used water balance model based on the basin scale, is first selected, and its widely accepted governing equations are applied. To understand the role of basin characteristics, Fu's equation is employed for the CONUS consisting of various vegetation, topography and soil types. A multiple regression model with a stepwise model selection method is adopted to define the relationship between basin characteristics and parameter in Fu's equation. Among five basin characteristics, including saturated

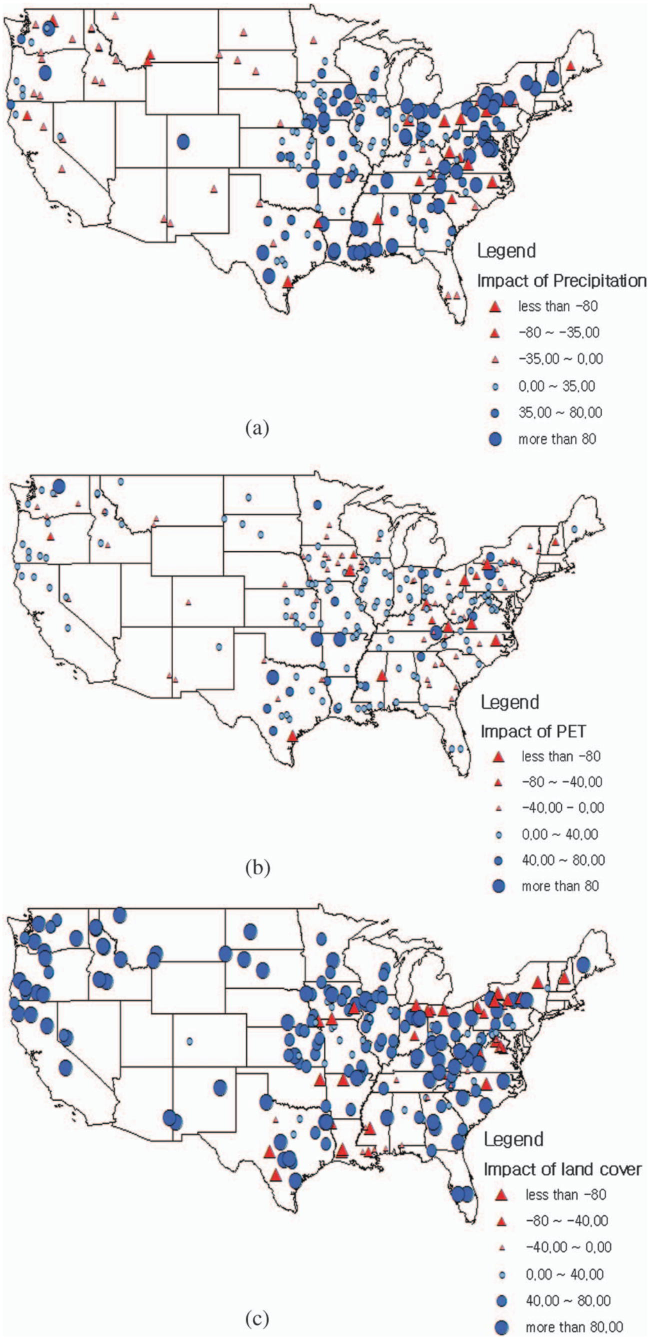

Figure 12.13. Contribution of annual streamflow change from: (a) precipitation change, (b) potential evapotranspiration change, and (c) land cover change

hydraulic conductivity, normalized difference vegetation index, basin area, basin slope, and stream length, three–the normalized difference vegetation index, the basin slope and the stream length–are chosen in the final equation based on the variable selection process (stepwise regression). The results show that the parameter in Fu's equation can be estimated by using the basin characteristics.

After recognition of the effect of basin characteristics on hydrology variables, the contribution method based on Choudhury's equation is applied to quantify the effect of change in the basin characteristics on streamflow change. Our study period (1950–1999) is divided into two sub-periods. Then, the change in streamflow from the first to second period is quantified by three impacts–precipitation, potential evapotranspiration, and change in basin characteristics. The results show that the change in basin characteristics is the most significant factor accounting for the change in streamflow in 225 basins of the CONUS. Its average contribution is 78.87%, whereas the contribution from climate variability is 21.13%.

This study should be viewed in light of the following limitations. It should be noted that the methodology used in this study cannot fully represent all basin conditions. Due to insufficient data, only five basin characteristics are considered in this study; basin area, slope, stream length, NDVI and saturated hydraulic conductivity. Therefore, one may not be able to extrapolate the findings of this study to other basins. Additionally, even though the basin characteristics used in this study are the most relevant for each basin, it is difficult to say that the values used for each basin completely represent all conditions in a basin, since a basin is formed by multitudinous terrain and geology.

Another potential limitation of this study is that the effect of changes in basin characteristics can be overestimated by using the contribution method. According to Yang et al. (2009) and Yokoo et al. (2008), the parameter '*n*' is also related to climate seasonality and daily mean storm depth. This may indicate that the value of the parameter '*n*' can be affected by climate variability. However, because estimation using basin characteristics is quite accurate, it is easy to conclude that the parameter '*n*' is independent of precipitation.

This study focused mainly on changes in annual values, but further studies of inter-annual or intra-annual scale should be conducted to confirm the results of this study.

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