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Testing the SEDD model in Sicilian basins

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Abstract The Sediment Delivery Distributed (SEDD) model combines the universal soil loss equation (USLE) or the revised universal soil loss equation (RUSLE) with a sediment delivery ratio to predict basin sediment yield. The model was applied to seven Sicilian basins, ranging in size from 20 to 213 km^2. Each basin has a reservoir located at its outlet. The model was applied to each basin using a raster scheme, and a subroutine of ArcInfo software to identify the hydraulic path linking each hillslope cell to the nearest stream cell, and to calculate both the travel time and the sediment delivery ratio of each cell. A procedure for estimating the β coefficient, which appears in the expression for determining the sediment delivery ratio of each cell, was developed. As the sedimentation volume for each of the seven reservoirs was known, it was possible to compare measured values with those calculated by the SEDD model. The agreement between measured sediment yield values and calculated ones confirmed the reliability of the proposed estimation procedure and indicates that it should be possible to apply the SEDD model to ungauged basins.

Key words distributed models; GIS; SEDD; sediment yield measurements; soil erosion; USLE

INTRODUCTION

Effective conservation planning requires the optimal allocation of land and water management practices within a basin, and has stimulated the use of spatially distributed sediment yield models coupled with Geographical Information Systems (GIS). At the basin scale, predicting sediment yield can be carried out coupling a soil erosion model with a mathematical function expressing the sediment transport efficiency of the hillslopes and the channel network (Walling, 1983; Bagarello *et al.*, 1991). If the process is studied at a mean annual temporal scale, the sediment transport efficiency of the hillslopes and the channel network is usually represented by the spatially lumped concept of the basin sediment delivery ratio SDR_w.

In order to apply a spatially distributed approach to evaluate sediment delivery processes, the basin must be divided into individual units having a regular (square or triangular cells) or irregular (morphological units) shape (Bagarello *et al.*, 1993). Then, the variables required for the equations associated with a process-oriented model, or the factors required for a parametric model such as USLE, can be calculated for each unit. USLE appears to be the best compromise between the availability of input data and the reliability of soil loss estimates (Risse *et al.*, 1993); further, this parametric model can easily be coupled with a spatial subdivision criterion to evaluate sediment delivery processes.

For a basin divided into morphological units (i.e. areas of clearly defined aspect, length and steepness) (Bagarello *et al.*, 1993), Ferro & Minacapilli (1995) proposed modelling the within-basin variability of hillslope sediment delivery processes using a sequential approach. Following a Lagrangian scheme, the sediment yield Y_i of each morphological unit, or square cell, is calculated first estimating soil loss by the USLE, and then applying an appropriate sediment delivery factor SDR_i to each sequential morphological unit (Novotny & Chesters, 1989).

Most previous applications of the SEDD model were carried out using a scheme which divided the basin into morphological units having an irregular shape that had been manually delimited on a topographic map. However, GIS software employs a raster scheme that divides a study area into square cells, having a known mesh size D; the numerical and alphanumeric information for each cell are stored by a matrix scheme. The raster scheme allows both an application of the SEDD model that is independent of the user, and reduces the calculation time.

In this paper, the analytical formulation of the SEDD model is briefly reviewed (Ferro & Porto, 2000), and then the model is applied to seven Sicilian basins with areas ranging from 20 to 213 km^2, each having a reservoir at its outlet. For each basin, the model was applied using a raster scheme, and a subroutine in ArcInfo software that individuated the hydraulic path linking each hillslope square cell to the nearest stream cell. For the investigated basins the relationship between the basin sediment delivery ratio SDR_w and some morphological variables, representative of sediment transport efficiency, was determined. Finally, a procedure for applying the SEDD model to ungauged basins was developed.

THE SEDIMENT DELIVERY DISTRIBUTED (SEDD) MODEL

For a basin divided into morphological units, and neglecting the channel component of the sediment delivery processes, Ferro & Minacapilli (1995) proposed to calculate the sediment delivery ratio SDR_i of each morphological unit using the following relationship:

$$SDR_i = \exp\left(-\beta\, t_{p,i}\right) = \exp\left(-\beta \frac{l_{p,i}}{\sqrt{s_{p,i}}}\right) = \exp\left(-\beta \sum_{j=1}^{N_p} \frac{\lambda_{i,j}}{\sqrt{s_{i,j}}}\right) \qquad (1)$$

where β is a coefficient; $t_{p,i}$ is the travel time of the particles eroded from a given hillslope cell to the nearest stream cell; N_p is the number of hillslope cells located along an hydraulic path having a length $l_{p,i}$ and a slope $s_{p,i}$; and $\lambda_{i,j}$ and $s_{i,j}$ are, respectively, the length and slope of each hillslope cell i localized along the hydraulic path j.

The sediment yield for each hillslope cell Y_i (t) is calculated from the following equation:

$$Y_i = R_i K_i LS_i C_i P_i SDR_i S_{u,i} \qquad (2)$$

where R_i (t ha^{-1} unit of k_i^{-1}) is the rainfall erosivity factor of the ith cell, K_i is the soil erodibility factor (t h kg^{-1} m^{-2}) estimated by the procedure of Wischmeier *et al.* (1971),

C_i is the cover and management factor, P_i is the support practice factor, and LS_i is the topographic factor. Three expressions are used for calculating the topographic factor. One is proposed for the original USLE model:

$$LS_i = \left(\frac{\lambda_i}{22.1}\right)^{0,5} \left(\frac{0.43 + 0.30\, s_i + 0.043\, s_i^2}{0.0896}\right) \tag{3}$$

where s_i is the slope, expressed as percent, of the hillslope cell; one proposed by McCool *et al.* (1989):

$$LS_i = \left(\frac{\lambda_i}{22.13}\right)^{m_i} (10.8 \sin\alpha_i + 0.03) \qquad \text{if } tan\alpha_i < 0.09 \tag{4a}$$

$$LS_i = \left(\frac{\lambda_i}{22.13}\right)^{m_i} (16.8 \sin\alpha_i - 0.5) \qquad \text{if } tan\alpha_i \geq 0.09 \tag{4b}$$

where the slope length exponent m_i has the following expression:

$$m_i = \frac{a\, f_i}{1 + a\, f_i} \tag{5}$$

where, according to McCool *et al.* (1989) and Di Stefano *et al.* (2000a), a coefficient is set equal to one and f_i has the following expression:

$$f_i = \frac{sen\,\alpha_i}{0.0896\left(3 sen^{0.8}\alpha_i + 0.56\right)} \tag{6}$$

and one proposed by Moore & Burch (1986):

$$LS_i = \left(\frac{\lambda_i}{22.13}\right)^{0.6} \left(\frac{\sin\alpha_i}{0.0896}\right)^{1.3} \tag{7}$$

The β coefficient of equation (1) is determined by applying the *sediment balance equation* at the basin outlet. This equation establishes that the basin sediment yield Y_s (t) is calculated by summing the sediment yield values Y_i for all the morphological units (square cells) into which the basin is divided:

$$Y_s = \sum_{i=1}^{N_u} SDR_i\, R_i K_i LS_i C_i P_i\, S_{u,i} = \sum_{i=1}^{N_u} \exp\left(-\beta\, t_{p,i}\right) R_i K_i LS_i C_i P_i\, S_{u,i} \tag{8}$$

where N_u is the number of hillslope cells into which the basin is divided.

The sediment balance equation applied at the basin outlet determines the sediment delivery relationship which relates the SDR_w and the sediment delivery ratio SDR_i for each hillslope cell. Ferro & Minacapilli (1995) have shown that the sediment delivery relationship is independent of the selected soil erosion model, and can be expressed only using morphological data:

$$SDR_w = \frac{\sum_{i=1}^{N_u} \exp(-\beta\, t_{p,i}) \lambda_i^{0.5}\, s_i^2\, S_{u,i}}{\sum_{i=1}^{N_u} \lambda_i^{0.5}\, s_i^2\, S_{u,i}} \tag{9}$$

THE STUDY BASINS AND APPLIED METHODS

In previous studies (Ferro *et al.*, 2003) the SEDD model was applied to six Sicilian basins, each having an area ranging from 20 to 70 km^2, and each with a reservoir located at the basin outlet. The sediment volume delivered to each reservoir, for a number of years, already had been determined.

According to previous studies (ASCE, 1975; Walling, 1983; Bagarello *et al.*, 1991), Ferro *et al.* (2003) found that the sediment delivery ratio for each basin could be estimated by applying the following:

$$SDR_w = \exp(-b \cdot S) \tag{10}$$

where S is the basin area expressed in km^2, and b is a numerical coefficient assuming a value quasi-independent of the expression used for the topographic factor (b = 0.0392 for USLE, b = 0.0328 for RUSLE and b = 0.0306 for the expression of Moore & Burch). For an ungauged basin, application of equation (10) allows an estimation of the basin sediment delivery ratio and using equation (9) an estimate, β_s, of β coefficient is obtained; in other words, the spatial distribution of the sediment yield can be established.

In this paper the SEDD model was applied to the six basins investigated by Ferro *et al.* (2003), as well as to the Gela a Disueri basin that has an area of 213 km^2. The sediment yield, delivered to the reservoir at the outlet of this last basin, had been established for the 1960–2001 period. For each basin in the study, Table 1 lists the basin area S (km^2), the mean hillslope slope s (%),the mean altitude H (m), and the mean annual sedimentation weight I (t ha^{-1} year^{-1}).

The digital elevation model (DEM) was obtained from topographic maps at a scale of 1:25 000, and a raster scheme, with a mesh size D, equal to 50 m. The slope and the aspect of each cell were calculated to estimate the topographic factor (LS_i) and the travel time $t_{p,i}$ into each hillslope cell (Borrough, 1996). Also, the stream network was extracted for each basin (Jenson & Domingue, 1988).

The topographic factor (equations (3), (4) and (7)) and the travel time into each cell were calculated using a slope length based on the aspect of the cell (D or 1.41D, according to the aspect). The hillslope travel time from a source cell i to a stream cell (Fig. 1) was obtained by summing the travel times $t_{p,i}$ of all cells i localized along the hillslope hydraulic path from the source to the stream cell. The hydraulic path was automatically plotted using the functions “spatial modelling” and “map algebra” in the ArcInfo software (Ferro *et al.*, 2003).

The rainfall erosivity factor R for the Gela a Disueri basin was calculated by the procedure of Bagarello & D’Asaro (1994). The procedure was applied at an annual scale using the historical sequence of daily rainfall measurements at the Piazza Marina raingauge located inside the basin. For the other six basins, the erosivity factor (R) was

Table 1 Characteristic data for the seven Sicilian basins.

Basin	S (km^2)	s (%)	H (m)	I (t ha^{-1} year^{-1})
Prizzi	19	17	770	13.9
Piana degli Albanesi	35	18	759	18.7
Rubino	40	13	315	2.7
Nicoletti	49	18	599	4.7
Ancipa	49	20	1245	7.4
Gammauta	69	28	820	6.9
Gela a Disueri	213	15	480	4.3

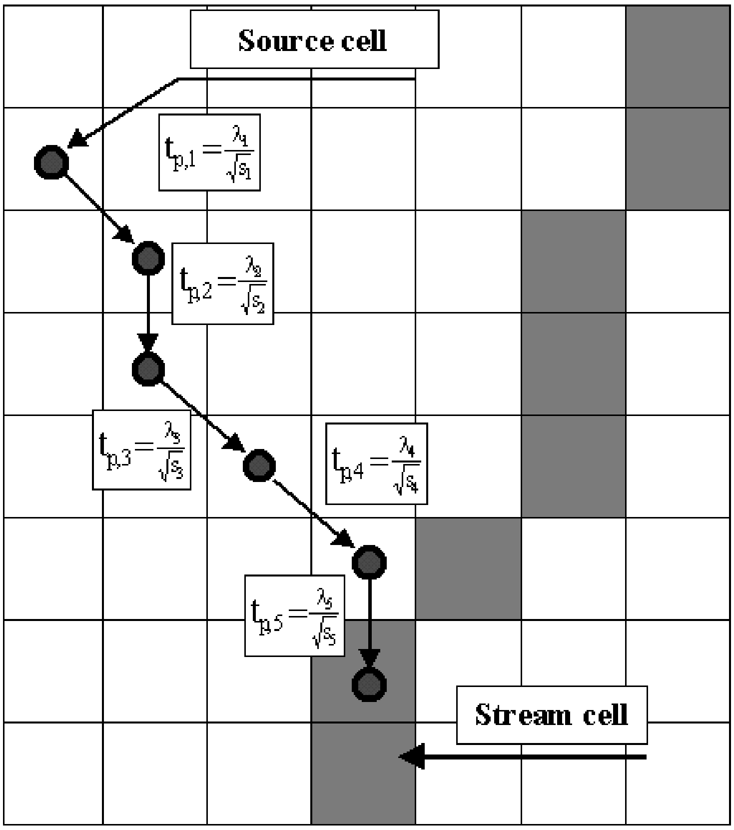

Fig. 1 Sketch for calculating the travel time.

obtained by digitizing the Sicilian isoerosivity map (Ferro *et al.*, 1991). The soil erodibility factor (K) was obtained using the Sicilian isoerodibility (iso-K) map (Giordano *et al.*, 2004).

For the Disueri basin, land-use data were obtained from a regional map (scale 1:250 000) developed by the Assessorato Territorio e Ambiente—Regione Siciliana. For the other six basins, evaluated in a previous paper (Ferro *et al.*, 2003), a Landsat TM image was used for allocating land use at a mesh size comparable with the one used for the DEM. The crop factor was estimated using information from Wischmeier & Smith (1978) and De Tar *et al.* (1980). No management practices have been carried out in any of the basins; hence, the support practice factor (P) was assumed equal to 1.

RESULTS

The SEDD model was applied to each of the seven study basins to estimate the soil erosion A (t ha^{-1} year^{-1}) in each basin, and its spatial distribution. In turn, the sediment yield value I (t ha^{-1} year^{-1}) was used to calculate the sediment delivery ratio SDR_w, equal to the ratio I/A, for each basin.

The sediment balance equation (8) was applied to each of the basins to obtain a value for the β coefficient corresponding to the condition $Y_s = I$ (Table 2). In addition, by basin, Table 2 contains the mean values for the USLE factors (R, K, LS, C), the mean annual soil loss A (t ha^{-1} year^{-1}), the β coefficient and the SDR_w values calculated as the ratio between the measured sediment yield I and the annual soil loss A. Based on data from the six original basins, and using different expressions of the topographic factor (equations (3), (4) and (7)), it was possible to develop an empirical relationship between the basin area (S) and the sediment delivery ratio SDR_w (Fig. 2). Note that the data from the Gela a Disueri basin appear to fall close to, but not on the curve of equation (10). This scattering can be explained by the fact that the original curve was developed for basins with areas <70 km^2, whereas the Gela a Disueri basin is 213 km^2.

Equation (11) is based on data from the seven Sicilian basins, and indicates the relationship between the basin sediment delivery ratio SDR_w and some morphological variables that are representative of sediment transport efficiency:

$$SDR_w = \exp(-b\ S) + a\ L + c \qquad (11)$$

where L is the total length of the river network (km), and a, b, and c are three coefficients whose value depends on the expression used for the topographic factor (Table 3).

Table 2 Results of the analysis carried out for the seven Sicilian basins.

Basin	Prizzi	Piana degli Albanesi	Rubino	Nicoletti	Ancipa	Gammauta	Gela a Disueri
R	45	45.2	30	80	50	50	76
K	0.442	0.512	0.489	0.532	0.544	0.431	0.481
LS (USLE)	5.3	9.3	4.2	5.4	6.6	13.38	4.7
LS (RUSLE)	3.8	5.2	3.1	4.4	5.3	7.23	3.6
LS (M&B)	3.5	4.6	2.8	3.9	4.7	6.68	3.5
C	0.401	0.392	0.243	0.208	0.337	0.329	0.324
A (USLE) (t ha^{-1} year^{-1})	38.7	74.6	10.8	34.2	58.3	72.7	46.0
A (RUSLE) (t ha^{-1} year^{-1})	28.1	41.7	8.6	34.4	47.2	43.82	39.0
A (M&B) (t ha^{-1} year^{-1})	25.5	38.4	7.8	30.7	41.4	40.16	35.2
β (USLE)	0.0015	0.0013	0.0018	0.0055	0.0060	0.0093	0.0072
β (RUSLE)	0.0008	0.0007	0.0014	0.0057	0.0049	0.0054	0.0063
β (M&B)	0.0007	0.0006	0.0013	0.0051	0.0044	0.0051	0.0060
SDR_w (USLE)	0.359	0.251	0.234	0.139	0.128	0.095	0.093
SDR_w (RUSLE)	0.495	0.432	0.292	0.138	0.158	0.157	0.110
SDR_w (M&B)	0.545	0.487	0.324	0.155	0.181	0.172	0.122

Table 3 Coefficients for equation (11).

Topographic factor	b	a	c
USLE	0.0392	0.00029	–0.0601
RUSLE	0.0328	0.00025	–0.0350
Moore & Burch	0.0306	0.00025	–0.0254

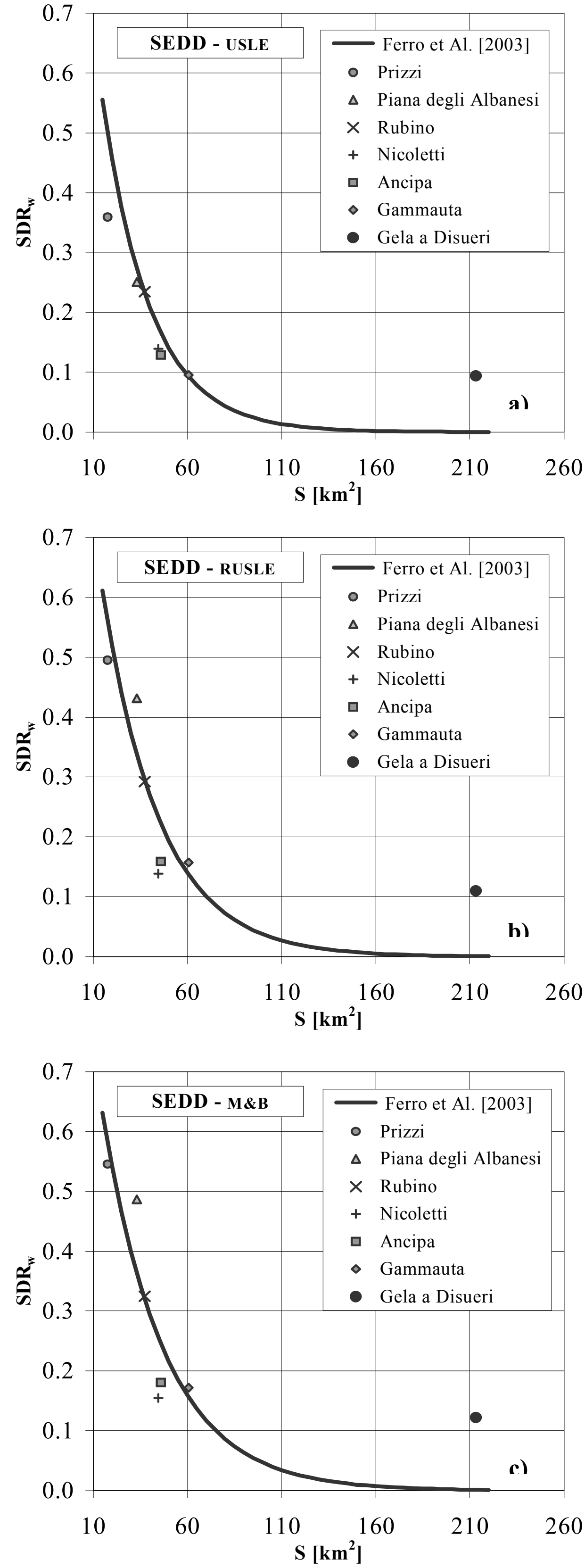

Fig. 2 Comparison between the pairs (S, SDR_w) of the investigated basins and equation (10).

Equation (11) can be used to estimate the basin sediment delivery ratio, and application of equation (9) generates estimate, β_s, of β coefficient. Application of equation (9) requires data on the slope length and steepness for each hillslope cell in the DEM.

Estimate β_s determined from different expressions of the topographic factors, is reasonably close to the β values for which $Y_s = I$ (Table 2). The comparison (Fig. 3) indicates that the best results are obtained using the topographic factors of RUSLE and Moore & Burch (1986). Finally, using β_s, equation (8) was used to calculate the basin sediment yields and their corresponding spatial distributions. There appears to be good agreement between the sediment yields calculated using equation (8) with $\beta = \beta_s$ and I, the measured sediment yield (Fig. 4). This would suggest that equations (9) and (11) could be used to estimate the β coefficient, and as such, could make it possible to apply the SEDD model to ungauged basins.

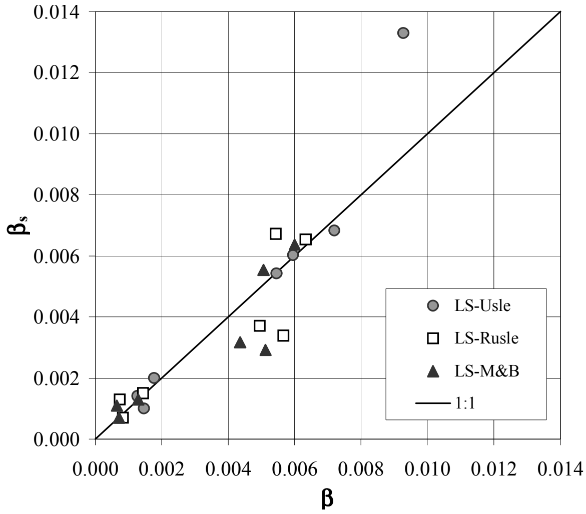

Fig. 3 Comparison between the estimates β_s, for the different topographic factors expressions, and the β values calculated by the sediment balance equation at the basin outlet (equation (8)).

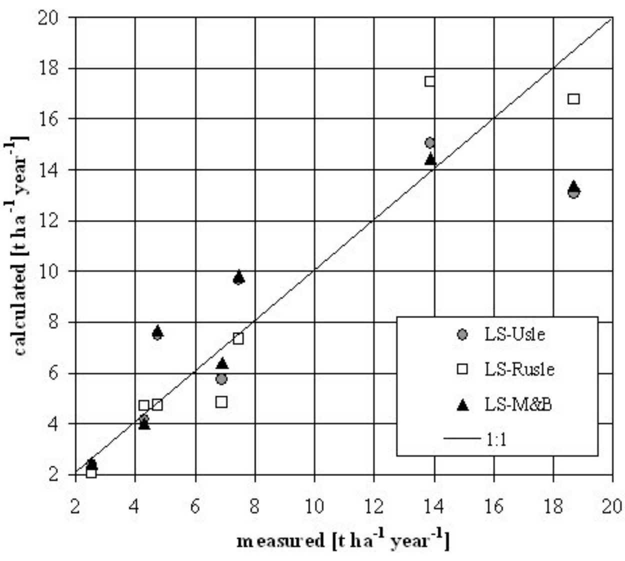

Fig. 4 Comparison between the sediment yield values, calculated by equation (8) and the estimates β_s, and the sedimentation volumes.

CONCLUSIONS

A soil erosion model, coupled with a mathematical function expressing sediment delivery processes, can be applied to identify areas within a basin where soil conservation strategies are required.

The SEDD (SEdiment Delivery Distributed) model, coupling USLE or RUSLE and the sediment delivery ratio of each morphological unit into which the basin is divided, has been tested at different spatial (small and large basins) and temporal (event, annual, mean annual) scales, and appears effective at estimating sediment yields and its spatial distribution.

Data from this study indicate that there is a relationship between the sediment delivery ratio SDR_w for a specific basin, and selected morphological variables (basin area, total length of river network) that represent the sediment transport efficiency. Within a basin, coupling this morphological relationship to estimate SDR_w, and the sediment balance equation (equation (9), sediment delivery relationship), it is possible to estimate the β coefficient, required in equation (1), for calculating the sediment delivery ratio of a morphological unit.

The good agreement, in the seven Sicilian basins, between measured sediment yield and that predicted by the SEDD model, confirms the reliability of this approach and indicates that the model might be applicable for estimating sediment yields in ungauged basins.

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