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Unmeasured Residuals in Sediment Budgets: A Cautionary Note

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In studies that develop sediment budgets, one or more terms (constituting up to 94% of the total budget) have been obtained by subtraction. These unmeasured residual terms incorporate not only the sediment budget components attributed to them, but also the net sum of all errors in measured components. Thus, budgets may appear to balance only because errors are hidden in the residual term. The nature of sediment measurements is such that some error is virtually certain, and in sediment budget studies where all terms have been quantified, imbalances range as high as 104% of total basin yield. Despite these potential problems, the process of constructing the budget is still informative (even when terms are obtained as residuals), because it requires sediment sources and transport pathways to be identified and quantified. However, terms obtained by subtraction should be clearly identified as such, and where possible, error analysis of all terms should be included.

INTRODUCTION

In studies that develop sediment budgets, it is often difficult to measure every term independently. As a result, in many such studies, one or more terms are obtained by subtraction. A variety of sediment budget components have been computed as residuals: alluvial storage, colluvial storage, fluvial erosion from hillslopes, suspended sediment passing over an upstream dam, and even total sediment yield from the watershed [*Lehre*, 1982; *Trimble*, 1983; *Best et al.*, 1991]. These unmeasured residuals (also called "garbage" terms) incorporate not only the sediment budget components attributed to them, but also the net sum of all errors in measured components. Thus, budgets may appear to balance only because errors are hidden in the residual term.

Such unmeasured residuals have been widely used not only in sediment budget studies, but also in water and nutrient budgets for lakes, and energy budgets for watersheds. Of the 23 water budget studies for lakes reviewed by *Winter* [1981], 15 calculated one of a variety of terms as residuals: evaporation, stream inflow and outflow, overland runoff, and groundwater inflow and outflow. *Winter* [1981, p. 83] noted that use of these residual terms produced a

> false sense of security about how well the budget is known. . . . Although lack of error analysis in most balance studies makes the residual term have little meaning, a great deal of interpretation and importance is sometimes given to a residual component.

In the phosphorus budget for a reservoir, *LaBaugh* [1985, p. 1691] explicitly acknowledged the uncertainty introduced by use of a residual term and concluded that the resulting uncertainty was so great that "interpretation of the reservoir's effect on incoming phosphorus could not be realistically evaluated." Such outright recognition of the residual problem has been rare in sediment budget studies.

In seven energy budgets for watersheds reviewed by *Cummins et al.* [1983], three computed at least one term by subtraction. The components of a watershed energy budget include detritus and photosynthesis (inputs), transport and respiration (outputs), and changes in storage. Because independent measurement of all these terms ". . . is such a laborious task, one or more parameters are routinely obtained by difference, and in no case has detrital storage been adequately examined, especially over greater than annual time periods." [*Cummins et al.*, 1983, p. 300]. In the four energy budgets for which all terms were independently measured or estimated, imbalances ranged from 5% to 47% [*Cummins et al.*, 1983].

RESIDUAL TERMS IN PUBLISHED SEDIMENT BUDGETS

A review of sediment budgets published in the geomorphic literature shows that a variety of components have been computed as residuals, and that these residual terms have, in cases, been quite large (Table 1).

Kelsey [1980] independently measured or estimated sediment yield from landsliding and bank erosion, and measured aggradation along major river channels and sediment export from the Van Duzen River basin (575 km^2) in California for the period 1941–1975. He also measured fluvial hillslope erosion from two landscape units: earthflow units with high sediment yields, and forested sandstone slopes with low sediment yields. Fluvial hillslope erosion from other units was computed as a residual. This residual term constituted 90.6% of total fluvial hillslope erosion, or 66.1% of the total sediment budget. The residually derived sediment yields from these other landscape units were considered reasonable because they were intermediate between the two "end-

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TABLE 1. Unmeasured Residuals Reported in Selected Sediment Budget Studies

Reference	Location	Period	Percentage of Total Computed as Residual	Attributed to
Kelsey [1980]	Van Duzen River, California	1941–1975	66.1	fluvial erosion from hillslopes
Kelsey et al. [1981]	Upper Redwood Creek, California	1956–1980	68	fluvial erosion from hillslopes
Lehre [1982]	Lone Tree Creek, California	1972, 1973, 1974	84, 44, 60	alluvial storage
Trimble [1983]	Coon Creek, Wisconsin	1853–1938, 1938–1975	36, 56	colluvial storage
Best et al. [1991]	Garrett Creek, California	1956–1980	94	sediment yield from basin
Matthews and Kondolf [1987]	Carmel River, California	1982, 1983	66, 34	alluvial storage and suspended load not trapped by upstream reservoir

members" represented by the rapidly eroding earthflow unit and the stable, forested sandstone slopes.

In a comprehensive study of sediment sources, storage, and transport in the upper Redwood Creek basin (720 km^2) of California, *Kelsey et al.* [1981] measured landslides, alluvial storage, and sediment export, to develop a sediment budget for 1956–1980. The increase in alluvially stored sediment and sediment flux from the basin exceeded measured inputs; the residual 68% was attributed to fluvial hillslope erosion.

In a detailed study of a small (1.7 km^2) watershed, *Lehre* [1982] measured landslides, gully erosion, soil creep, sheet erosion, bank erosion, and sediment yield from the basin. He attributed the difference between sediment delivered to channels and the yield from the basin to alluvial storage; in 1972 this residual was equal to 84% of the total budget. *Trimble* [1983] reconstructed sediment yield from tributaries and upland sheet and gully erosion, as well as sediment yield from the watershed (360 km^2) of Coon Creek, Wisconsin, for two periods: 1853–1938, and 1938–1975. For each period the largest component in the budget, colluvial storage, was calculated as a residual.

Matthews [1987] and *Matthews and Kondolf* [1987] measured sediment yield of the mainstem and tributaries of the Carmel River, California (660 km^2) from sediment sampling, and measured bank erosion from aerial photographs and field surveys for 1982 and 1983 (Table 2). These data were broken down into suspended and bed load components. Differences between total yield from the basin and the sum of tributary and bank erosion sources were attributed primarily to alluvial storage (for bed load), and to sediment passing over an upstream dam (for suspended load). The trends in bed load sediment storage agree with limited field observations for the period, but the residual suspended load was substantially larger than estimates of suspended load passing over the dam derived from reservoir sedimentation rates and trap efficiencies.

Best et al. [1991] measured sediment sources and channel storage for Garrett Creek, California, for 1956–1980, but sediment output from the basin (11 km^2) for this period had not been measured. The increase in alluvial storage was 6% of the total inputs. The residual 94% of total inputs was attributed to export from the basin. This sediment yield was comparable to better constrained estimates from similar, gaged basins nearby.

IMBALANCES IN PUBLISHED SEDIMENT BUDGETS

In budgets where all components have been quantified (measured or estimated), we have calculated net imbalances, defining total basin output as 100% (Table 3). The relative magnitude of the imbalances appears to be greatest when infrequent processes, short study periods, or low sediment yields are involved.

TABLE 2. Sediment Budget for Carmel River Below San Clemente Dam, 1982 and 1983

	1982			1983		
	Suspended Load	Bed Load	Total	Suspended Load	Bed Load	Total
Output	199	118	317	1120	326	1446
Inputs						
Tributaries	13	5	18	217	39	256
Bank erosion	27	64	91	210	489	699
Total	40	69	109	427	528	955
Balance[a]	159	49	208	693	(202)[b]	491
Estimated load over dam	86	···	···	430	···	···
Unexplained balance	73	···	···	263	···	···

All values in tonnes (1 tonne equals 1000 kg). Table entries represented by three dots correspond to data categories which are not applicable.

[a]Attributed to in-channel storage changes and suspended sediment passing over San Clemente Dam.

[b]Balance is negative, indicating a net sink of bed load–sized sediment into in-channel storage.

TABLE 3. Imbalances in Selected Sediment Budget Studies

Reference	Location	Period	Imbalance as Percentage of Total Basin Export	Comments
Madej [1982]	Big Beef Creek, Washington	1971–1976	8–104	Bed load transport from basin, computed using three different formulae, was 49, 75, and 118% of sum of bed load inputs.
Swanson et al. [1987]	Watershed 10, H.J. Andrews Forest, Oregon	long-term average conditions	20	Sum of inputs of inorganic material was 20% greater than the sum of outputs.
Weaver et al. [1991]	Lower Redwood Creek, California	1954–1980	10	Sum of inputs less change in channel storage exceeded output from basin by 10%.
K. M. Nolan (personal communication, 1991)	four tributaries to Lake Tahoe, California	1984–1987	1–45	Inputs, storage changes, and export measured over 4 years. Largest imbalances in small basins with low sediment yields.

Madej [1982] measured or estimated sediment production from landslides, soil creep, road surface sheetwash, and bed load transport in the Big Beef Creek watershed (38 km^2) in Washington, but did not explicitly address in-channel storage changes. She resolved sediment inputs into suspended and bed load components, and computed bed load export from the basin using three equations. The bed load export values predicted by these equations were 49%, 75%, and 118%, respectively, of the estimated input to the channel. If we define basin export as 100% (consistent with other studies), the imbalances become 104%, 33%, and 8% respectively.

Weaver et al. [1991] developed a sediment budget for Lower Redwood Creek (197 km^2) for 1954–1980, using measurements of gully erosion, landslides, and sediment loads above and below the study area. The sum of inputs less storage was only 10% less than export from the basin, a remarkably small net error given the lack of precision in sediment measurements. Of course, potentially larger individual errors may have been self-canceling.

Swanson et al. [1987] measured processes of solution transfer, surface erosion, creep, root throw, debris avalanche, earthflow, and sediment export from Watershed 10 (0.1 km^2) in the H. J. Andrews Experimental Forest in Oregon. The total of all inorganic sediment inputs was 20% greater than the total inorganic sediment export from the basin.

K. M. Nolan (U.S. Geological Survey, Menlo Park, personal communication, 1991) measured mass wasting, sheet erosion, bank erosion, in-channel storage changes, and net export from four basins tributary to Lake Tahoe, California, over a 4-year period, from 1984 to 1987. The sum of sediment inputs less storage changes differed from total sediment export by 1% to 45%. Imbalances were smallest in the larger basins of the west shore, with higher precipitation and higher sediment yields. Imbalances were greatest in the smaller basins of the east shore, with less precipitation and lower sediment yields. As was noted with respect to *Weaver et al.* [1991], the smallest net imbalance of 1% may not reflect potentially larger, self-canceling errors.

DISCUSSION

It should come as no surprise when sediment budgets do not balance, because accurate measurements are difficult or impossible for many components. Imbalances appear in all budgets for which enough terms have been quantified to balance the budget. These net errors range from 1% to over 100% of the total sediment export. Budgets in which one term is obtained by subtraction probably have comparable errors, but the errors are hidden in the residual term.

In many cases, it is impossible to measure one or more components of the sediment budget. For example, in Garrett Creek [*Best et al.*, 1991] components such as landslides were reconstructed from field evidence and historic aerial photographs from 1956 to 1980, but without a downstream reservoir or historical measurements, there was simply no way to reconstruct past sediment export from the basin.

Unmeasured components can be estimated using rates derived from studies elsewhere, but this may be appropriate only for a "first cut" at the problem. Rates of processes such as bank erosion can vary by orders of magnitude within one basin or at one site from year to year. For example, sediment yield from Tularcitos Creek, a tributary to the Carmel River, increased 50-fold from 1982 to 1983 as a result of abruptly increased rates of bank erosion. The increase in sediment yield was not simply due to higher runoff, but was the result of a threshold response, reflected in a large shift in the sediment rating curves for the stream [*Matthews*, 1983]. If "standard" rates for other studies were applied to this site, important changes would have been missed.

When rates derived elsewhere are used to develop large components of the budget, the uncertainty increases. *Trimble*'s [1983] largest sediment source, upland erosion, was computed using the universal soil loss equation [*Soil Conservation Service*, 1975]. This component was 500% greater than the sum of all other source components; thus, a subtle change in input values used in the equation could change the resulting sediment source component by an amount greater than the sum of the other source terms.

Without detailed error analysis [*LaBaugh*, 1985], it is impossible to evaluate the magnitude of error in budgets that use residual terms, because these residuals incorporate not only the components to which they are attributed, but also the net error of the other terms. The magnitude of net error can be quite large, as indicated by imbalances in other sediment budgets in the literature for which enough terms were quantified to permit us to calculate imbalances.

Resolution of the sediment budget into suspended and bed load components is not routinely done, but it can shed light on the routing of sediment through a basin in general. Specifically, this information can set constraints on the possible sources for unmeasured terms. For example, in the sediment budget for the Carmel River (Table 2), the balance terms could be more precisely attributed because they were broken down into suspended and bed load components. The suspended load balance could be attributed to (1) sediment passing through a small upstream reservoir, which would trap all bed load, and (2) unknown net error. The bed load balance could be attributed to (1) erosion of channel bed and bars, which are composed of sand and gravel, with relatively little suspendable material, and (2) unknown net error.

CONCLUSIONS

Our intent is not to discourage construction of sediment budgets, even those in which terms are obtained by subtraction. The exercise of constructing the sediment budget is useful because it requires that sediment sources and transport pathways be identified and, to the extent possible, quantified [*Dietrich and Dunne*, 1978]. Even budgets based on incomplete information can provide an indication of the relative importance of different sources and linkages.

However, sediment budget components obtained by subtraction should be clearly identified as such, and these values should be treated differently than the independently measured data from which they were derived. Moreover, the fact that accumulated errors from measured terms are hidden in these residuals deserves mention so that managers and policy makers are not misled about the precision of such sediment budgets. This is particularly so when the residual value is the variable of interest. Where possible, error analysis of each term should be included, as advocated for water and nutrient budgets by *Winter* [1981] and *LaBaugh* [1985].

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REFERENCES

Best, D. W., H. M. Kelsey, D. K. Hagens, and M. Alpert, Role of fluvial hillslope erosion and road construction in the sediment budget of Garrett Creek, Humboldt County, California, Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California, edited by K. M. Nolan, D. Marron, and H. M. Kelsey, *U.S. Geol. Surv. Prof. Pap.*, *1454*, in press, 1991.

Cummins, K. W., J. R. Sedell, F. J. Swanson, G. W. Minshall, S. G. Fisher, C. E. Cushing, R. C. Peterson, and R. L. Vannote, Organic matter budgets for stream ecosystems: Problems in their evaluation, in *Stream Ecology: Applications and Testing of General Ecological Theory*, pp. 299–353, Plenum, New York, 1983.

Dietrich, W. E., and T. Dunne, Sediment budget for a small catchment in mountainous terrain, *Z. Geomorphol. Suppl.*, *29*, 191–206, 1978.

Kelsey, H. M., A sediment budget and an analysis of geomorphic process in the Van Duzen River basin, north coastal California, 1941–1975, *Geol. Soc. Am. Bull.*, *Part 2*, *91*, 1119–1216, 1980.

Kelsey, H. M., M. A. Madej, J. Pitlick, M. Coghlin, D. Best, R. Belding, and P. Stroud, Sediment sources and sediment transport in the Redwood Creek basin: A progress report, 114 pp., Redwood Natl. Park, Arcata, Calif., 1981.

LaBaugh, J. W., Uncertainty in phosphorus retention, Williams Fork Reservoir, Colorado, *Water Resour. Res.*, *21*, 1684–1692, 1985.

Lehre, A. K., Sediment budget of a small coast range drainage in north central California, Sediment Budgets and Routing in Forested Drainage Basins, edited by F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanston, *Gen. Tech. Rep. PNW-141*, pp. 67–77, Pac. Northwest For. and Range Exp. Stn., U.S. For. Serv., Portland, Oreg., 1982.

Madej, M. A., Sediment transport and channel changes in an aggrading stream in the Puget Lowland, Washington, Sediment Budgets and Routing in Forested Drainage Basins, edited by F. J. Swanson, R. J. Janda, T. Dunne, and D. N. Swanston, *Gen. Tech. Rep. PNW-141*, pp. 97–108, Pac. Northwest For. and Range Exp. Stn., U.S. For. Serv., Portland, Oreg., 1982.

Matthews, W. V. G., Discharge and sediment load for tributaries to the Carmel River, *Working Pap. 5*, Monterey Peninsula Water Manage. Dist., Monterey, Calif., 1983.

Matthews, W. V. G., Evaluation of the effects of the feasible New San Clemente project alternatives on the channel stability and sediment transport of the Carmel River, *Tech. Memo. 87-13*, *Monterey Peninsula Water Manage. Dist.*, *Monterey, Calif.*, 1987.

Matthews, W. V. G., and G. M. Kondolf, Changes in sediment storage over time on a coastal California river, *IAHS Publ.*, *165*, 413–414, 1987.

Soil Conservation Service (SCS), Procedures for computing sheet and rill erosion of project areas, *SCS Tech. Release*, *51*, U.S. Dep. of Agric., Washington, D. C., 1975.

Swanson, F. J., G. E. Grant, and G. W. Lienkaemper, Field guide to the H. J. Andrews Experimental Forest, guidebook for premeeting field trip, International Association of Hydrological Sciences meeting, Corvallis, Oreg., Aug. 1987.

Trimble, S. W., A sediment budget for Coon Creek basin in the driftless area, Wisconsin, 1853–1977, *Am. J. Sci.*, *283*, 454–474, 1983.

Weaver, W. E., D. K. Hagens, and J. H. Popenoe, Magnitude and causes of gully erosion in the Lower Redwood Creek drainage basin, Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California, edited by K. M. Nolan, D. Marron, and H. M. Kelsey, *U.S. Geol. Surv. Prof. Pap.*, *1454*, in press, 1991.

Winter, T. C., Uncertainties in estimating the water balance of lakes, *Water Resour. Bull.*, *17*, 82–115, 1981.

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Comment on "On the Fractal Interpretation of the Mainstream Length–Drainage Area Relationship" by A. Robert and A. G. Roy

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Robert and Roy [1990] examine the fractal interpretation of the relationship between mainstream length L, and catchment area A

$$L = aA^b \tag{1}$$

and find that the value of the exponent b is not a constant, as would be required by the fractal interpretation of this relationship, but varies with the scale of measurement. They also give a table of the corresponding values of a. The purpose of this comment is to note that their measurements of a appear consistent with a fractal interpretation of the river network based on Horton's laws and their extension to catchment areas [*Tarboton et al.*, 1988; *La Barbera and Rosso*, 1989].

Consider an Nth order basin with R_B, R_L, R_A as the branching ratio, stream length ratio, and basin area ratio, respectively. Fractal dimensions may be assigned to these as

$$D_1 = \frac{\log (R_B)}{\log (R_L)} \qquad D_2 = 2\,\frac{\log (R_L)}{\log (R_A)} \tag{2}$$

Fractal geometry indicates that the subbasin of order n has a length-area relationship

$$L_n = SA_n^{D_2/2} \tag{3}$$

where S is a constant. This relationship expressed in terms of order-1 channels (i.e., the smallest), is thus

$$R_L^{n-1}L_1 = SR_A^{(n-1)D_2/2}A_1^{D_2/2} \tag{4}$$

The mainstream channel length is given by the sum of the N subbasins, each of length L_n. Thus

$$L = L_1\,\frac{R_L^N - 1}{R_L - 1} \tag{5}$$

By contrast, the total catchment area is given by

$$A = A_N = A_1 R_A^{N-1} \tag{6}$$

If we now assume self-similarity between the mainstream length–total catchment area, and the subbasin length–subbasin area, then (1) and (4) should be the same. This requires

$$b' = D_2/2 \tag{7}$$

$$a' = SR_L^{1-N}\left(\frac{R_L^N - 1}{R_L - 1}\right) \tag{8}$$

where the prime indicates that these are the values to be expected if fractal similarity holds.

The important point to note about (8) is that even if the mainstream length–drainage area relationship of (1) is indeed a fractal, so that the exponent b is a constant (and equal to one half of the fractal dimension D_2), the constant a will be scale-dependent because N, the order of the catchment, is itself a scale-dependent quantity. Let us explicitly represent the effects of scale on the variables and parameters with the

TABLE 1. Values of $a'(s)/a'(20)$ for Values of the Stream Length Ratio

R_L	$a'(50)/a'(20)$	$a'(125)/a'(20)$
1.010	0.545	0.238
1.020	0.641	0.319
1.030	0.704	0.384
1.040	0.748	0.437
1.050	0.781	0.482
1.060	0.806	0.521
1.070	0.826	0.554
1.080	0.842	0.583
1.090	0.856	0.608
1.100	0.867	0.630
1.110	0.877	0.650
1.120	0.885	0.668
1.130	0.892	0.685
1.140	0.899	0.699
1.150	0.905	0.713
1.160	0.910	0.725
1.170	0.914	0.736
1.180	0.918	0.746
1.190	0.922	0.756
1.200	0.926	0.765
1.300	0.948	0.828
1.400	0.960	0.864
1.500	0.968	0.888
1.600	0.973	0.904
1.700	0.977	0.917
1.800	0.980	0.926
1.900	0.982	0.934
2.000	0.984	0.940
2.100	0.985	0.945
2.200	0.986	0.949
2.300	0.987	0.953
2.400	0.988	0.956
2.500	0.989	0.959
2.600	0.990	0.961
2.700	0.990	0.964
2.800	0.991	0.966
2.900	0.991	0.967
3.000	0.992	0.969

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notation $a(s)$ where s is the length scale variation on the parameter a.

The length scale will be proportional to L_1. Robert and Roy assume that their limit of resolution is 1 mm so that s is 20 m, 50 m, and 125 m for the map scales that they use. The numbers given by *Smith and Stopp* [1978, p. 43] for Dartmoor granite catchments indicate that $L_1 = 22s$, approximately. Thus the value of N, the catchment order, can be determined from (5), provided R_L is known. This is not given by *Robert and Roy* [1990] who give, instead, values for the fractal dimensions as $D_1 = 1.085$ and $D_2 = 1.2$. Using these results, I have prepared Table 1, which shows the variation of $a'(s)/a'$ (20) for $s = 50$ and $s = 125$.

Robert and Roy find that $a(50)/a(20) = 0.57$ and $a(125)/a(20) = 0.52$. However, before these values can be compared to those given in Table 1, it is necessary to remove the effect of scale on b. Robert and Roy indicate that $b(20) = 0.546$, $b(50) = 0.635$ and $b(125) = 0.648$. The effect of the change in exponent will dominate the $a(s)/a(20)$ ratio, which is given by

$$\frac{\hat{a}(s)}{\hat{a}(q)} = \frac{L(s)A(s)^{-b(s)}}{L(q)A(q)^{-b(q)}} \tag{9}$$

where q represents a reference scale ($q = 20$ in this case), and the hat symbol indicates that these are the values to be expected as a result of allometry. I have deduced expected allometric values of the ratio $\hat{a}(s)/\hat{a}(q)$, by using (9) and the data for the length and area in Table 1 of Robert and Roy for each of their 22 basins to calculate a value of $\hat{a}(s)/\hat{a}(q)$ and averaging. This produces $\langle\hat{a}(50)/\hat{a}(20)\rangle = 0.65$ and $\langle\hat{a}(125)/\hat{a}(20)\rangle = 0.53$. One would expect the observed value to be the product of the fractal and allometric contributions such that

$$\frac{a(s)}{a(q)} = \frac{a'(s)}{a'(q)}\frac{\hat{a}(s)}{\hat{a}(q)} \tag{10}$$

The results do not fit (10) exactly, but appear consistent (within statistical variability) for a basin with a value of R_L of about 1.7.

References

La Barbera, P. and R. Rosso, On the fractal dimension of stream networks, *Water Resour. Res.*, *25*, 735–741, 1989.

Robert, A., and A. G. Roy, On the fractal interpretation of the mainstream length–drainage area relationship, *Water Resour. Res.*, *26*, 839–842, 1990.

Smith, D. I., and P. Stopp, *The River Basin*, Cambridge University Press, New York, 1978.

Tarboton, D. G., R. L. Bras, and I. Rodriguez-Iturbe, The fractal nature of river networks, *Water Resour. Res.*, *24*, 1317–1322, 1988.

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