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Determination of sediment yields in the Vacacaí-Mirim River basin using MUSLE

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Abstract The objective of this study was to determine sediment yields in the Vacacaí-Mirim watershed which has an area of some 1150 km^2, and which lies between 29°36′55″–29°39′50″S and 53°46′30″–53°49′29″W. Estimates were made using the Modified Universal Soil Loss Equation (MUSLE) in conjunction with the Williams & Berndt sediment routing model. The catchment was divided into 93 sub-basins, with drainage areas ranging from 0.7 to 115 km^2. The MUSLE parameters were determined in the 93 sub-basins; three sub-basins, representative of the three physiographic provinces in the catchment, were selected for the determination of William's routing coefficient. Requisite data were obtained from a combination of sources (e.g. satellite imagery; national army maps) and entered into a GIS database. The Soil Conservation Service curve number methodology and the Santa Maria rainfall equations developed by Belinazo & Paiva were used to generate hydrographs for the study area. Based on a 50-year return flow, maximum discharge ranged from 7.69 to 567.14 m^3 s^{-1} and flow volumes ranged from 23 193.75 to 11 983 872 m^3. Estimated sediment yields ranged from 0.02 to 0.84 t ha^{-1}.

Key words Brazil; sediment yield, small watersheds; Vacacaí-Mirim River basin

INTRODUCTION

Erosion and sediment transport are natural processes that occur as a result of rainfall; however, their rates can be directly related to land-use. As such, land-use changes can accelerate erosion and subsequent sediment transport due to physical landscape modifications and concomitant changes in the flow regime of a watershed. Erosion and sedimentation can substantially degrade the land surface. For example, in agricultural areas, erosion can lead to a loss of fertility/productivity and in urban areas depositional zones can severely limit construction. A thorough knowledge of sediment yield and transport should be viewed as a requisite for adequate water resource management. Hence, methods for measuring and/or predicting rates of erosion (sediment yield) and subsequent fluvial sediment fluxes have become more and more relevant.

The Vacacaí-Mirim River basin is one of the most important watersheds in the Santa Maria region of Brazil. Hence, a thorough knowledge of local patterns of erosion (sediment yield) and sediment transport are a requisite for adequate watershed management. To that end, the Modified Universal Soil Loss Equation (MUSLE), in conjunction with the Williams & Berndt (1977) sediment routing model, were applied to the river basin as an aid to watershed management, and as a guide for future research. The results of that modelling exercise are reported herein.

METHODOLOGY

The Vacacaí-Mirim River basin is a tributary of the Jacui River, which in turn, is part of the Guaiba River basin. It has an area of some 1150 km^2 and is located between 29º36′55″–29°39′50″S and 53º46′30″–53°49′29″W. The Guaiba River basin is the largest in the state of Rio Grande do Sul. Cartographic data for the study were managed by GIS compatible IDRISI 32 software and were contained in four separate map layers that covered: (a) soil/land type and land use; (b) contours; (c) drainage; and (d) sub-basins.

The locations of representative soil types within the basin were identified, and specific locations noted, using GIS. This permitted subsequent field location and sampling using a portable Global Positioning System (GPS) unit. Soil samples were analysed for grain-size distribution following the procedures outlined in Associação Brasileira de Normas Técnicas 7181 (ABNT, 1984). This Brazilian Technical Standard describes methods for physical soil analyses including sieving and sedimentation.

Maximum discharges and flow volumes were determined from hydrographs generated by using the Soil Conservation Service curve number methodology and the Santa Maria rainfall equations developed by Belinazo & Paiva (1991) along with watershed hydraulic characteristics; the peak flow rate (Q_P) was calculated by:

$$Q_p = \frac{0.27K \cdot H_u \cdot A}{T_p'} \quad (1)$$

where Q_p is the peak flow rate (m^3 s^{-1}); K is a peak factor: 1.0 for high-slope and 0.5 for low-slope and 0.75 for medium-slope watersheds; A is the watershed area (km^2); T_p' is the peak period (h); and H_u is a useful parcel of the total rain (mm).

The rainfall intensity (I) was calculated by the Santa Maria rainfall equation:

$$I = \frac{807.801 \cdot Tr^{0.1443}}{(t + 5.67)^{0.7472 Tr^{-0.028}}} \quad (2)$$

where I is rainfall intensity (mm h^{-1}); Tr is the return period (years); and t is the rainfall duration (min).

Sediment yield was calculated by dividing the study area into 93 sub-basins, where the Modified Universal Soil Loss Equation (MUSLE) was applied in conjunction with the Williams & Berndt (1972) flow-path model, for isolated events. The equation is:

$$Y = \alpha (Q_s \cdot q_p)^{\beta} \cdot K \cdot LS \cdot C \cdot P \quad (3)$$

where Y is the sediment yield to an individual rainfall event in tonnes; Q_s is the surface flow volume (m^3); q_p is the surface flow peak (m^3 s^{-1}); α and β are coefficients that were calibrated to the specific basin (89.6 and 0.56); and K, LS, C and P are soil erodibility, topographic (representing both slope length and steepness), crop management and conservation practices factors, respectively.

The Vacacaí-Mirim River basin can be divided into three physiographic regions as well as into 93 sub-basins. The three physiographic regions are: (a) the “Planalto” that represents the elevated portion of the basin; (b) the “Rebordo do Planalto” that represents the hillside areas; and (c) the Central Depression, delineated by the flat portion of the basin (Fig. 1). A representative sub-basin from each of the three physiographic regions was then selected for application of the Williams (1975) routing model, which was used to further subdivide each representative sub-basin in which the amount of sediment yield, caused by an isolated rainfall event, was estimated using the MUSLE. Total sediment yield for each representative sub-basin is the sum of the individual estimates for the smaller sub-basins from the most upstream location to the outlet. The routing model assumes a certain level of sediment loss between each of the smaller sub-basins due to deposition.

According to Williams (1975), the loss rate depends on the particle-size distribution of the soil, and the velocity of the overland flow, as well as on the course length and period; it can be expressed as:

$$\frac{\mathrm{d}y}{\mathrm{d}t} = -B \cdot Y\sqrt{D} \tag{4}$$

where dy/dt is loss rate at time t; Y is sediment yield in a watershed specific section (t ha^{-1} s^{-1}); t is time (h); B is a routing coefficient; and D is the particle diameter (mm).

Integrating equation (4), and solving for Y, yields:

$$Y = Y_0 \mathrm{e}^{-B \cdot T \sqrt{D}} \tag{5}$$

where Y_0 is the sediment yield in an upstream section (t); and T is the course period between the two sections (h).

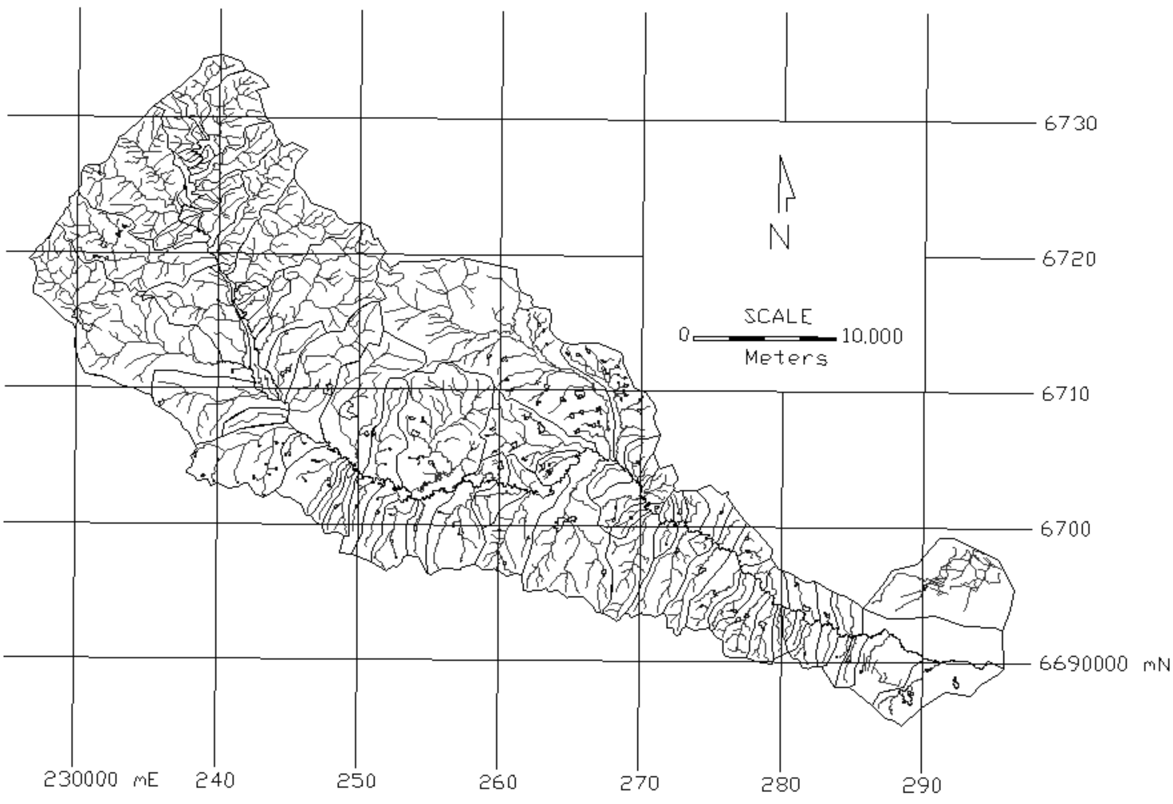

Fig. 1 The study area divided into sub-basins and the drainage distribution. UTM (datum SAD 69) coordinates system; the drainage is in grey and the sub-basin divisions are in black.

To determine the total amount of sediment routed through the sub-basin between its most upstream end and its outlet, the contribution from each sub-basin is summed according to:

$$RY = \sum_{i=1}^{n} Y_i \cdot \mathrm{e}^{-B \cdot T \sqrt{D_{50}}} \qquad (6)$$

where RY is the sediment yield for the representative sub-basin (t); Y_i is the sediment yield for each sub-basin (t); B is the routing coefficient; T_i is the course period between the ith sub-basin and the watershed outlet (h); D_{50} is the ith sub-basin median sediment particle diameter (mm); and n is the number of sub-basins.

The determination of the B coefficient for an individual rainfall event in a particular watershed assumes uniform distribution of the following parameters: K, LS, C, P and D_{50}, then Y calculated using equation (3) is the same as RY calculated using equation (6).

Determination of the routing (B) coefficient for an individual rainfall event, in a particular watershed, assumes that the MUSLE K, LS, C, P and D_{50} parameters are uniform throughout the sub-basin. Then, the sediment yield (Y) for the representative sub-basin can be estimated using equation (3), and is the same as RY in equation (6).

$$89.6(Q_S \cdot q_p)^{0.56} \cdot K \cdot LS \cdot C \cdot P = 89.6 \sum_{i=1}^{n} (Q_{S_i} \cdot q_{pi})^{0.56} \cdot K_i \cdot LS_i \cdot C_i \cdot P_i \cdot \mathrm{e}^{-B \cdot T_i \sqrt{D_{50i}}} \qquad (7)$$

where Q_s is the surface flow volume (m^3); q_p is the surface peak flow (m^3 s^{-1}); Q_{si} is the surface flow volume in the sub-basin (m^3); q_{pi} is the surface peak flow in the sub-basin (m^3 s^{-1}); B is the routing coefficient; T_i is the time between the ith sub-basin and the watershed outlet (h); and D_{50i} is the ith sub-basin median sediment particle diameter. The terms K, LS, C, P are soil erodibility, topographic (representing both slope length and steepness), crop management and conservation practices factors, respectively.

In each of the chosen sub-basins, the K, LS, C and P values were considered similar to all the smaller sub-basins that flow into it; thus, they cancel each other out in equation (7), resulting in a routing coefficient (B) determination equation.

$$(Q \cdot q_p)^{0.56} = \sum_{i=1}^{n} (Q_i \cdot q_{pi})^{0.56} \cdot \mathrm{e}^{-B \cdot T_i \sqrt{D_{50m}}} \qquad (8)$$

where Q is the surface flow volume (m^3); q_p is the surface peak flow (m^3 s^{-1}); Q_i is the surface flow volume in the sub-basin (m^3); q_{pi} is the surface peak flow in the sub-basin (m^3 s^{-1}); B is the routing coefficient; T_i is the course period between the ith sub-basin and the watershed outlet (h); and D_{50m} is the ith sub-basin median sediment particle diameter (mm).

Table 1 Calculated routing parameters in the selected representative sub-basins.

Region	Sub-basin	Routing parameter (B)
Planalto	31	14.82
Rebordo do Planalto	87	11.52
Depressão central	68	53.96

Table 2 Estimated sediment yields, based on MUSLE, for the Vacacaí-Mirim sub-basins.

Sub-basin	Area (km^2)	Q_s (m^3)	q_p (m^3 s^{-1})	K	LS	C	P	Y (t ha^{-1})	Y (mm)
1 C	14.16	855873.72	94.85	0.0554	1.9496	0.0035	0.7283	0.47	0.0177
2 C	8.34	466042.90	53.70	0.0420	1.8583	0.0028	0.8077	0.27	0.0100
3 C	7.12	403101.94	44.99	0.0416	2.2581	0.0028	0.8112	0.31	0.0117
4 C	51.26	2850419.38	332.42	0.0553	3.3760	0.0027	0.8217	0.76	0.0288
5 C	7.84	458247.28	47.25	0.0424	0.8265	0.0026	0.8253	0.11	0.0042
6 C	10.17	610817.29	54.35	0.0387	2.3561	0.0024	0.8547	0.27	0.0100
7 C	5.42	247476.99	19.74	0.0442	0.4410	0.0036	0.7191	0.05	0.0018
8 C	26.74	1644867.23	137.63	0.0378	3.2558	0.0023	0.8632	0.39	0.0146
9 C	4.17	187831.35	28.25	0.0427	0.8707	0.0014	0.9605	0.06	0.0024
10 C	29.79	2455292.06	219.55	0.0470	8.3887	0.0030	0.7970	2.19	0.0828
11 C	3.84	214279.44	24.78	0.0392	1.6223	0.0026	0.8272	0.19	0.0071
12 C	44.59	3178335.60	178.69	0.0419	1.3779	0.0022	0.8663	0.18	0.0068
13 C	5.14	223280.32	22.03	0.0619	0.3968	0.0038	0.6941	0.06	0.0024
14 C	23.49	2157660.92	99.16	0.0423	1.0735	0.0054	0.5095	0.22	0.0084
15 C	15.37	879315.14	81.74	0.0352	3.2146	0.0021	0.9150	0.32	0.0122
16 C	4.43	176022.67	17.28	0.0364	0.4070	0.0029	0.7982	0.03	0.0011
17 C	4.70	240674.30	29.25	0.0610	0.8374	0.0022	0.8854	0.13	0.0048
18 C	4.73	223236.59	38.10	0.0573	1.9598	0.0031	0.7890	0.39	0.0148
19 C	19.94	1161352.68	103.22	0.0447	1.2104	0.0017	0.9199	0.13	0.0049
20 C	19.98	1299686.81	93.89	0.0451	1.2922	0.0021	0.8872	0.16	0.0061
21 C	6.50	436739.51	31.31	0.0465	0.5983	0.0029	0.7942	0.09	0.0033
22 C	22.64	1450294.93	118.14	0.0659	0.9741	0.0026	0.8302	0.22	0.0083
23 B	0.84	27415.91	12.01	0.0153	7.6569	0.0017	0.9705	0.25	0.0096
24 B	2.39	114028.27	27.54	0.0305	7.8927	0.0018	0.9535	0.66	0.0248
25 A	0.86	32525.57	11.15	0.0201	8.6694	0.0018	0.9973	0.41	0.0155
26 B	37.07	2829911.66	224.02	0.0261	12.4117	0.0018	0.9741	1.19	0.0448
27 A	0.82	28985.20	11.15	0.0140	8.5966	0.0015	1.0000	0.23	0.0088
28 B	2.66	125274.75	28.80	0.0163	15.4362	0.0015	0.9966	0.60	0.0225
29 A	11.09	651043.24	83.92	0.0322	1.0980	0.0501	0.5018	1.54	0.0582
30 C	27.52	1321412.85	99.27	0.0565	0.4978	0.0118	0.8207	0.31	0.0118
31 A	7.86	443599.32	46.14	0.0281	4.3248	0.0250	0.7675	3.31	0.1248
32 A	42.04	2990353.80	304.89	0.0220	16.1893	0.0127	0.8820	8.84	0.3336
33 A	0.66	26968.63	8.68	0.0298	6.7617	0.0012	0.9973	0.33	0.0124
34 A	2.67	128894.13	35.26	0.0376	4.0155	0.0021	0.9002	0.50	0.0189
35 B	2.08	114774.01	25.93	0.0417	4.5162	0.0028	0.8190	0.79	0.0296
36 B	5.15	326807.20	46.97	0.0313	6.4354	0.0022	0.8992	0.72	0.0272
37 C	10.37	519823.32	97.42	0.0546	3.5639	0.0039	0.6934	0.94	0.0354
38 C	25.98	1992232.10	231.24	0.0442	8.8272	0.0032	0.7795	2.39	0.0902
39 B	43.75	3454824.02	294.34	0.0314	16.1451	0.0019	0.9255	2.07	0.0779
40 B	32.38	2398614.38	221.55	0.0286	18.9086	0.0017	0.9519	1.89	0.0714
41 C	76.53	6012377.88	561.62	0.0381	13.4289	0.0062	0.9404	7.61	0.2871
42 B	0.72	23193.75	10.37	0.0306	11.6943	0.0015	0.9889	0.68	0.0258
43 C	34.63	3040566.49	249.14	0.0512	6.4428	0.0031	0.7815	1.94	0.0731
44 C	5.31	210669.38	38.73	0.0575	0.2978	0.0063	0.4196	0.06	0.0021
45 C	2.85	166447.67	17.20	0.0328	0.6512	0.0028	0.8127	0.06	0.0024
46 C	1.74	88731.93	11.77	0.0348	0.5107	0.0019	0.9116	0.04	0.0014
47 C	2.13	69870.22	9.31	0.0344	0.4758	0.0016	0.9519	0.02	0.0007
48 C	4.54	247239.65	30.33	0.0357	1.1967	0.0024	0.8485	0.12	0.0047
49 C	3.54	134054.38	18.74	0.0506	0.4531	0.0040	0.6761	0.06	0.0023

Sub-basin	Area (km^2)	Q_s (m^3)	q_p (m^3 s^{-1})	K	LS	C	P	Y (t ha^{-1})	Y (mm)
50 C	2.32	63190.65	11.70	0.0391	0.3882	0.0016	0.9562	0.02	0.0006
51 C	5.47	266404.79	22.54	0.0347	0.5190	0.0049	0.5715	0.05	0.0019
52 C	6.39	413197.54	41.60	0.0343	0.8003	0.0041	0.6564	0.12	0.0044
53 C	9.65	424903.60	37.38	0.0356	0.5137	0.0034	0.7303	0.05	0.0017
54 C	5.45	272116.30	37.89	0.0409	2.6312	0.0020	0.9007	0.27	0.0100
55 C	3.23	146560.77	21.69	0.0367	1.0079	0.0013	0.9757	0.06	0.0021
56 C	45.78	3637289.55	205.86	0.0471	1.8400	0.0010	0.6600	0.10	0.0039
57 C	4.12	228631.52	26.80	0.0405	0.8879	0.0027	0.8192	0.11	0.0041
58 C	15.69	614643.00	85.43	0.0529	0.4947	0.0047	0.6000	0.09	0.0033
59 C	20.20	1012437.24	72.92	0.0604	0.3334	0.0045	0.5982	0.06	0.0023
60 C	5.82	280747.89	26.42	0.0502	0.4935	0.0054	0.5190	0.07	0.0028
61 C	23.93	2042288.33	118.33	0.0521	1.0487	0.0055	0.5110	0.28	0.0107
62 C	3.49	182848.62	24.59	0.0374	0.9314	0.0025	0.8347	0.10	0.0038
63 C	3.08	115566.85	34.17	0.0503	1.1423	0.0030	0.7755	0.19	0.0073
64 C	4.85	232495.91	41.36	0.0332	3.1487	0.0032	0.7731	0.39	0.0146
65 C	7.39	310279.65	26.43	0.0395	0.5459	0.0026	0.8278	0.04	0.0016
66 C	0.74	27523.68	7.69	0.0398	1.0656	0.0027	0.8284	0.11	0.0041
67 C	3.27	163646.38	26.43	0.0406	1.0656	0.0030	0.7850	0.15	0.0055
68 C	17.24	1056876.45	104.46	0.0372	3.3799	0.0063	0.8988	1.18	0.0447
69 C	0.90	31988.95	14.04	0.0175	9.4015	0.0107	0.9005	2.30	0.0868
70 A	115.50	11983872.39	567.14	0.0426	10.0895	0.0027	0.8306	2.37	0.0894
71 A	19.28	1054341.37	109.52	0.0290	4.8640	0.0115	0.8796	2.18	0.0822
72 B	2.58	119230.58	32.94	0.0170	12.3993	0.0158	0.8670	4.96	0.1871
73 C	1.40	59116.28	11.02	0.0475	1.4932	0.0016	0.9488	0.12	0.0046
74 C	10.40	660573.85	55.03	0.0352	2.2745	0.0023	0.8574	0.24	0.0090
75 C	1.71	67847.66	15.50	0.0351	1.7330	0.0022	0.8739	0.14	0.0055
76 C	9.78	652241.49	65.47	0.0355	0.9799	0.0046	0.6035	0.17	0.0062
77 C	5.40	254833.97	40.31	0.0407	0.6261	0.0019	0.8948	0.06	0.0024
78 C	3.67	155086.90	17.79	0.0496	0.4583	0.0044	0.6233	0.06	0.0023
79 C	3.25	186851.30	29.61	0.0402	0.7203	0.0146	0.8402	0.59	0.0221
80 C	2.10	93142.53	18.20	0.0436	2.3608	0.0024	0.8531	0.27	0.0103
81 C	5.85	321888.94	44.97	0.0474	1.1001	0.0035	0.7337	0.21	0.0079
82 C	3.91	199919.61	30.73	0.0409	2.4460	0.0031	0.7782	0.36	0.0134
83 B	6.86	365105.46	70.93	0.0259	18.2817	0.0016	0.9793	1.34	0.0507
84 B	0.83	31859.17	11.44	0.0341	5.9794	0.0018	0.9493	0.49	0.0186
85 B	20.29	1554342.63	142.95	0.0332	6.2697	0.0027	0.9073	1.07	0.0405
86 A	11.54	591886.68	66.27	0.0278	4.1773	0.0038	0.9557	0.59	0.0221
87 B	4.01	218161.43	40.51	0.0252	11.1825	0.0022	0.9646	1.03	0.0389
88 C	13.58	724827.53	86.31	0.0389	2.8144	0.0020	0.8927	0.30	0.0115
89 C	5.80	296863.44	36.11	0.0376	2.7724	0.0018	0.9197	0.23	0.0086
90 C	1.66	87618.32	20.20	0.0333	1.4399	0.0038	0.7057	0.22	0.0082
91 C	4.59	282002.11	35.05	0.0358	1.0625	0.0044	0.6258	0.17	0.0064
92 B	1.57	63367.38	19.39	0.0170	7.5363	0.0015	0.9838	0.29	0.0109
93 B	1.02	40614.96	13.68	0.0338	9.4370	0.0019	0.9376	0.81	0.0304

Q_s: flow volume; q_p: peak flow rate; K, LS, C and P: the MUSLE factors; Y: sediment volume.
[A] Sub-basins representative of the Planalto region.
[B] Sub-basins representative of the "Rebordo do Planalto" region.
[C] Sub-basins representative of the Central Depression region.

RESULTS AND CONCLUSIONS

As noted previously, the Vacacaí-Mirim River basin can be subdivided into three distinct physiographic regions (Planalto, Rebordo do Planalto, and the Central Depression). The routing parameter (B) was estimated for each physiographic region (Table 1). When B is used in conjunction with MUSLE, it was possible to estimate the sediment yields for all 93 sub-basins within the catchment for a single event, using the Santa Maria rainfall equation (Belinazo & Paiva, 1991) and the Soil Conservation Service (SCS) curve number method (Table 2). Estimated sediment yields range from 0.03 to 18 t ha^{-1} (Table 2). The use of GIS software made the selection and physical location of the requisite soil sampling sites relatively simple. It also provided a means for identifying the three representative sub-basins that were used in estimating the routing parameter (B) (Williams & Berndt, 1977). The estimated values for B, 14.82, 11.52, and 53.96 for the Planalto region, the Rebordo do Planalto region, and the Central Depression, respectively, are wholly dependent on the sites selected to represent the three regions. It should be borne in mind that these estimates of B are wholly dependent on the assumption that the local hydraulic and soil characteristics are homogeneous within a sub-basin.

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