WATER RESOURCES RESEARCH, VOL. 39, NO. 4, 1082, doi:10.1029/2002WR001521, 2003

Distributed assessment of contributing area and riparian buffering along stream networks

Brian L. McGlynn

Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, Montana, USA

Jan Seibert

Department of Environmental Assessment, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden

Received 17 June 2002; revised 18 October 2002; accepted 4 February 2003; published 2 April 2003.

[1] We present a simple approach for quantifying the local contributions of hillslope area and riparian area along a stream network based on gridded digital elevation data. The method enables one to compute catchment characteristics such as the distribution of riparian and hillslope inputs to the stream network, the variation of riparian-area percentage along the stream network, and subcatchment area distributions. We applied the technique to the 280-ha Maimai research area in New Zealand. We found that 85% of the catchment area contributed to streams with a local catchment area of <20 ha, whereas only 28% of the riparian area was found along these small streams. The potential of riparian zones to buffer hillslope runoff depends partially on the size of the riparian zone relative to the adjacent hillslope or upland area. Our approach enables calculation of a spatially distributed measure of riparian to hillslope area ratios. At the 280 ha Maimai research area we found that the ratio between riparian and hillslope area was 0.14. When we calculated this "buffer capacity" for each 20 m stream reach along the stream network, the values were below 0.14 for 75% of the stream length and the median was 0.06. Using the catchment-wide ratio would thus significantly overestimate the "effective" riparian-to-hillslope-area ratio. *INDEX TERMS:* 1824 Hydrology: Geomorphology (1625); 1848 Hydrology: Networks; 1860 Hydrology: Runoff and streamflow; *KEYWORDS:* riparian, hillslope, topography, buffer, Maimai, landscape analysis, stream network

Citation: McGlynn, B. L., and J. Seibert, Distributed assessment of contributing area and riparian buffering along stream networks, *Water Resour. Res.*, *39*(4), 1082, doi:10.1029/2002WR001521, 2003.

1. Introduction

[2] The riparian zone encompasses the strip of land between the stream channel and the hillslope and is sometimes referred to as a buffer zone [*Lowrance et al.*, 1985], floodplain [*Bates et al.*, 2000], or near-stream zone [*Cirmo and McDonnell*, 1997]. Riparian zones have been differentiated from upslope zones by unique hydrology, vegetation, and soils [*Hill*, 1996]. Characteristics such as anoxic zones [*Megonigal et al.*, 1993], gleyed soils [*Phillips et al.*, 2001], color [*Blavet et al.*, 2000], organic content [*Mitsch and Gosselink*, 1993], breaks in slope [*Merot et al.*, 1995], and near-surface water tables [*Brinson*, 1993] often distinguish riparian zones from adjacent uplands. Because of their location, riparian zones have significant potential to regulate the movement of material in surface and subsurface runoff that flows from upslope areas to the stream [*Brinson et al.*, 1981; *Hill*, 1996]. Subsurface solute inputs from adjacent uplands are influenced by the magnitude of flow into riparian zones [*Devito*, 1995].

[3] Hillslope inputs to riparian zones are spatially variable along stream networks [*Weyman*, 1970]. Runoff is not generated uniformly across hillslope cross-sections partially due to topographical convergence and divergence [*Freeze*, 1972]. Accumulation of upslope area [*Anderson and Burt*, 1978; *Beven*, 1978] often determines variability of hillslope inputs along stream networks. As a result, area entering the stream network is variable from stream reach to stream reach.

[4] In shallow soil systems with poorly permeable bedrock, hillslope and riparian dynamics are predominantly controlled by topography. Variability in, and controls of, hillslope inputs to stream networks have not been examined in the context of riparian zone function and the potential modulating capacity of riparian zones. While the flushing of riparian zones by hillslope runoff is a first-order control on potential chemical transformation [*Hill*, 1990] and hillslope water expression in streamflow [*Hooper et al.*, 1997; *McGlynn et al.*, 1999; *Burns et al.*, 2001; *McGlynn and McDonnell*, 2003], little is known about the ratio of the upslope (hillslope) inputs to the local riparian zone storage. Significant uncertainties exist about the role riparian zones play in regulating water and element movement from uplands to streams, despite much work on individual hillslope and riparian cross sections (transects). Furthermore, the spatial distribution of riparian zones, especially relative to upland area accumulation, has received little attention so far. This inhibits our ability to

0043-1397/03/2002WR001521$09.00

move forward and assess the role of riparian zones in a catchment context.

[5] Accumulated area maps can show us where hollows and streams are located. Slope maps can show us where flat valley bottom areas are distributed. Combined, as in the TOPMODEL index [*Beven and Kirkby*, 1979], such calculations can indicate which parts of a catchment might be more likely to be surface-saturated. None of these indices, however, tell us much about the catchment function in the context of the distribution and connection of dominant landscape units. We present a new landscape assessment technique for objective mapping and quantification of dominant landscape units (i.e., hillslopes and riparian zones), simple evaluation of riparian zones, and quantification of hillslope-riparian area interactions. The approach allows for characterization of the distribution of hillslope and riparian area along the stream network based on DEM analysis of upslope contributing area. It also enables apportionment of landscapes into their riparian and hillslope components, providing the framework for assessment of the modulating (buffer) potential of riparian zones and subsequent hillslope-riparian-stream-catchment connections. We illustrate this technique using the Maimai research area in New Zealand as an example. Existing maps and tools have shown us that flat valley bottom areas are relatively large along the main axis of the Maimai catchment and decrease toward the headwaters. Similar observations have been made for many other catchments [*Gregory and Walling*, 1973]. However, techniques to quantify the frequency and distribution of riparian areas have been previously unavailable.

2. Physical Characteristics of the Maimai Catchment

[6] The Maimai study area consists of more than 8 formerly or currently gauged catchments located to the east of the Paparoa mountain range on the West Coast of the South Island of New Zealand (42°05′S, 171°48′E). We limited our analysis to the 280 ha Maimai research watershed named the Bedload catchment. The subcatchments share similar topographic characteristics. Slopes are short (<300 m) and steep (average 34°) with a local relief of 100–150 m. Stream channels are incised and lower portions of the slope profiles are convex. All the catchments are underlain by moderately weathered, firmly compacted lower Pleistocene Old Man Gravels, which are effectively impermeable [*Mosley*, 1982]. Soils are classified as Blackball hill soils and are shallow (~1 m deep), strongly podsolized yellow-brown earths with a well-developed upper organic humus mantle with a mean depth of 17cm [*Mew et al.*, 1975]. Hillslope slope angles in headwater catchments range from 30°–45° and catchment side slopes are composed of regular spurs and linear hollows. Historical research at the Maimai catchments has focused on the development of a highly detailed perceptual model of hillslope hydrology (recently reviewed by *McGlynn et al.* [2002]).

[7] Maimai is a suitable site for development of new techniques for topographic analyses because the landscape is simple relative to many research catchments [*Woods and Sivapalan*, 1997]. The geology is uniform, the topography is steep and highly dissected, soil depths are relatively uniform, and topography has been found to control the shallow through flow. The topography is characterized by few sinks (i.e., grid cells with no neighboring cell with lower elevation than itself) and a clear distinction between riparian zones and hillslopes.

3. Our New Method

[8] We computed the stream network for the Maimai catchment using a digital elevation model and a creek-threshold-area method. Upslope area can be computed from DEMs in different ways [*Quinn et al.*, 1995; *Tarboton*, 1997]. Multiple-flow-direction algorithms tend to provide more realistic looking spatial patterns than single-direction algorithms, where all area from one cell is routed into the steepest of its eight neighboring cells. The latter tend to result in too strong a concentration of flow, which is avoided by distributing the flow among several downslope neighboring cells. Another problem with single-flow-direction algorithms is that the steepest gradient actually might fall between two of the eight cardinal and diagonal directions. *Tarboton* [1997] addressed this problem using triangular facets, which remove the limitation of only eight possible directions. Our method combines the advantages of the multiflow-direction algorithm [*Quinn et al.*, 1995] with the use of triangular facets (J. Seibert, manuscript in preparation, 2003).

[9] Once the accumulated area exceeded the threshold value, this area was routed downslope as a "creek-area" and all cells along the downslope flow path were flagged as "creek cells". For routing the creek-area we used a single-direction algorithm. Using this simple approach, at several instances parallel streams were computed in adjacent cells. To avoid an unrealistic stream network, we used an iterative procedure. Any creek cell where we derived more than one adjacent creek cell in a downslope direction was, in the next iteration, forced to drain to the downslope creek cell with the largest accumulated area. This procedure was repeated until a stream network without "parallel" streams was obtained (usually 2–5 iterations are necessary).

[10] The creek initiation threshold area was estimated as 0.5 ha based on field surveys of channel initiation points in 30% of the Bedload headwater catchments. It should be noted that a creek threshold area of 0.5 ha is probably the lower boundary of accumulated area for channel initiation. Often channels are initiated at the confluence of more than one convergent hillslope zone each having accumulated area below the 0.5 ha threshold, but resulting in initial creek accumulated area >0.5 ha. We based field measured channel initiation points on morphological indicators as set forth by *Dietrich and Dunne* [1993]. This provided confirmation even in the absence of flow, such as indications of ephemeral channels including a scoured streambed, definable channel banks, and an incision into the ground surface, since the channel head was not always synonymous with the stream head. The stream head simply indicates the upstream extent of concentrated surface runoff at a particular time [*Dietrich and Dunne*, 1993] and may migrate up and down the channel depending on catchment moisture and runoff rates [*Hewlett and Hibbert*, 1967; *Dunne*, 1978].

[11] We surveyed riparian widths at intervals as small as 10 m, perpendicular to the stream channel from the Bedload weir to the point of channel initiation in multiple head-

water catchments. Riparian-hillslope boundaries were determined in the field based on breaks in slope (i.e., valley bottoms between the stream and the abrupt break in slope at the hillslope boundary), soil characteristics (i.e., gleying, organic accumulation, color, and texture), and terrain characteristics. We measured the width of the riparian zone, the width of the stream channel, and soil depths across each transect. We then computed the corresponding accumulated catchment area for each transect-stream channel intersection and tried to correlate the two variables. At Maimai, the variations of the width of the riparian zone could be explained to 99.2% by the accumulated catchment area using simple linear regression (Figure 1). This simple method for estimation of riparian width is not generally transferable to other catchments. When the riparian width is not determined by an accumulated catchment area relationship, riparian width might be estimated by morphometric rules (e.g., a threshold elevation above the stream channel along flow paths to the stream), remote sensing, or field mapping. If an alternative riparian area estimation technique is used, the steps outlined in the flowchart (Figure 2) are still applicable. Development of the riparian width catchment area relationship step would be bypassed in this case. Our approach simply requires a riparian area or width association with each stream cell in the channel network.

[12] Based on the computed linear regression between catchment area and field surveyed riparian widths, we calculated the riparian area for each stream cell. By multiplying the length of the cell by the estimated width of the riparian zone we estimated the local riparian zone area for each stream cell. Integrating riparian area associated with each stream cell in an upstream direction gives the total riparian area for the catchment defined by the downstream stream cell. The area entering the stream network at each stream cell, i.e., the local area inputs to the channel network, are the incremental increases in catchment area for each stream cell. Incremental increases in catchment area along the stream network are a combination of hillslope and riparian areas. Since we calculated the riparian area for each stream cell, the difference between total incremental area increase for each stream cell (not including downstream inputs) and local riparian area associated with each stream cell is equal to hillslope area inputs for that stream cell.

[13] Following the steps outlined above, we generated 5 different coverages (see flowchart in Figure 2): (1) total local inflow to each stream cell, (2) local riparian area along the stream network (Figures 3b and 4b), (3) local hillslope area entering the stream network (Figures 3c and 4c), (4) accumulated riparian area as a fraction of catchment area, and (5) riparian to hillslope area ratios along the stream network (Figures 3d and 4d). These analyses allow for distributed evaluation of local riparian to hillslope area ratios (R/H) at each point along the stream network, a ratio suggested as a first-order control on hillslope water expression in catchment runoff [*Hooper et al.*, 1997; *McGlynn et al.*, 1999; *Burns et al.*, 2001]. In order to translate these distributed "area" values to flow, one has to assume that specific discharge is constant over the catchment (although this assumption easily can be relaxed if there is information available about the spatial distribution of specific discharge). This assumption is seldom correct, but for the case of Maimai it is an appropriate approximation because specific runoff is almost constant across catchment scale as determined by records of runoff from weirs at >8 catchment scales [*Mosley*, 1979; *Pearce et al.*, 1986; *McGlynn et al.*, 2002].

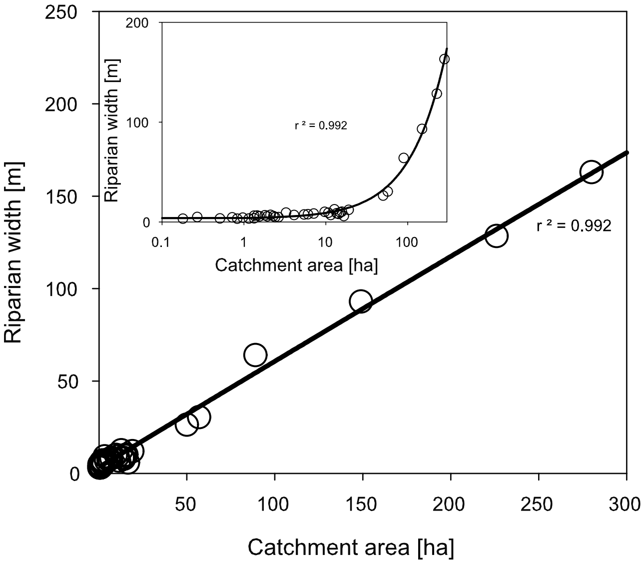

Figure 1. Riparian width versus local catchment area. Data are based on 42 surveyed transects in multiple headwater catchments and at different locations along the main valley axis. The inset plot shows the same data but with log-scale for the catchment area.

4. Results and Discussion

[14] While computed stream networks derived from digital elevation data might not always agree with the real network exactly [e.g., *Zhang and Montgomery*, 1994], we found a good agreement for the Maimai landscape due to its distinct topography (Figure 3a). For other landscapes with more muted topography and lower drainage densities, techniques that use the real network to "correct" the elevation data might be appropriate.

[15] Local hillslope area inputs to the stream network varied between 0 and 1.1 ha (values larger than the creek-initiation threshold of 0.5 ha are due to multiple sub-0.5 ha hollows converging at one channel cell) (Figure 3c) and were mainly distributed nearly uniformly between 0 and 0.65 ha (Figure 4c). In general hillslope area accumulation was greatest at the channel heads (Figure 4c). The channel heads are typically high hillslope accumulated areas due to bowl shaped convergent headwaters in many of the Maimai streams.

[16] We computed the accumulated catchment area (Figure 5) along the channel network and found that 35% of the Bedload catchment (280 ha) area originates in subcatchments smaller than 1 ha, 60% in <4 ha subcatchments, and 85% in <20 ha subcatchments. The break-in-slope of the total accumulated area versus originating catchment scale plot (Figure 5, inset) differentiates the area accumulated in headwater catchments from the area accumulated along the main stem of the river. This information is also presented in histogram form (Figure 4a). The shape of this curve means that most area is accumulated in the smallest headwater

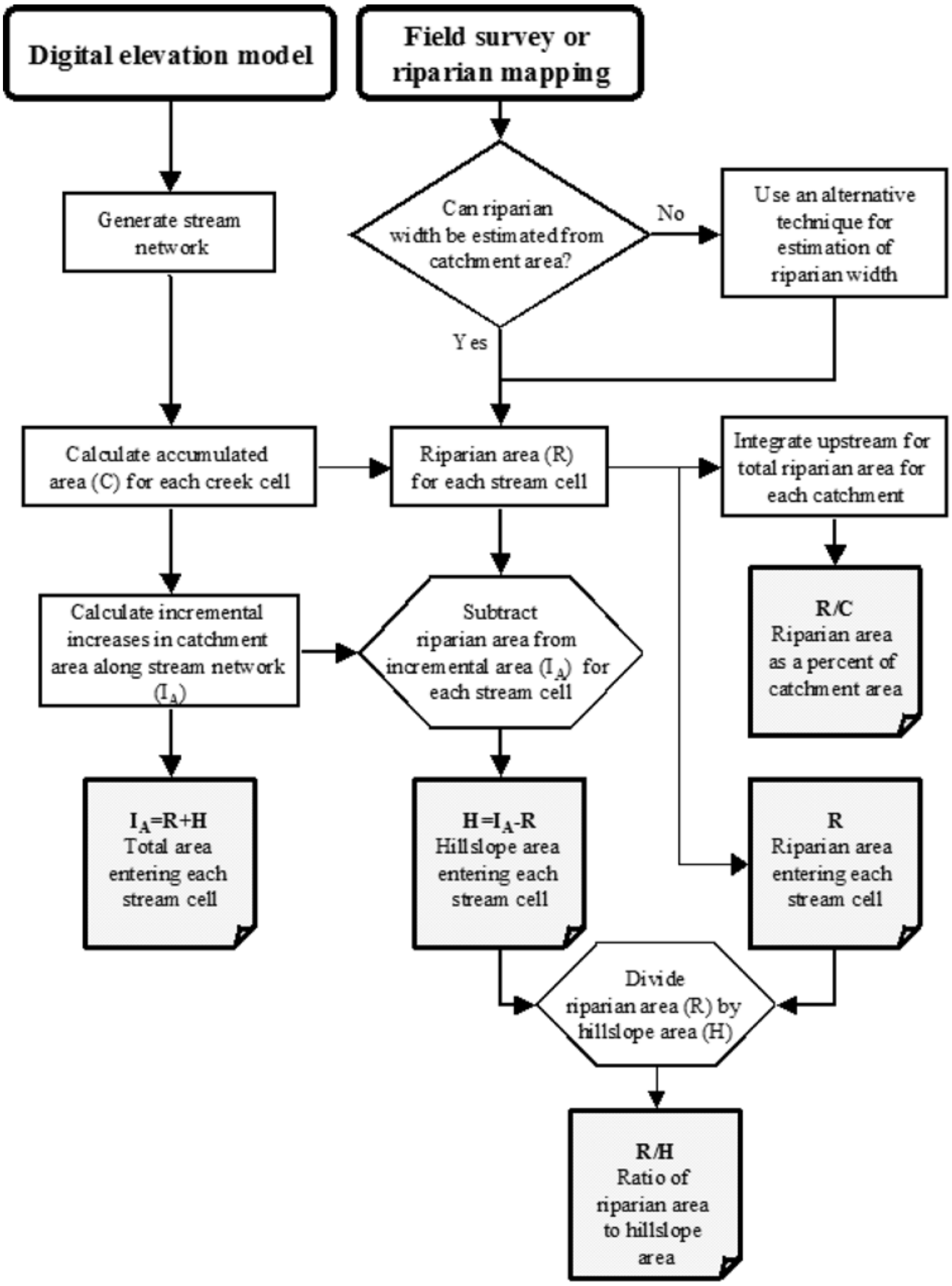

Figure 2. Flowchart of the proposed approach for landscape analysis and riparian assessment technique.

catchments and enters the main stem of the river via defined tributary junctions. Relatively little area enters the stream network through wider valley bottom riparian zones along the main stem (~15%), similar to the hypothetical third- and fourth-order basins described by *Leopold et al.* [1992] who suggested that ~20% enters the main stem directly and 80% enters via first- and second-order tributaries. Similarly, *Wondzell* [1994] found that the proportion of catchment area draining directly into first- through fifth-order channels in the 62 km^2 ha Lookout Creek catchment at HJ Andrews Experimental Forest in Oregon was: 66% of area drains into first-order channels, 16% into second-order channels, 10% into third-order channels, 4% into fourth-order channels, and 4% into fifth-order channels.

[17] We found that the median local catchment size of all stream cells was 3.2 ha, while the mean was 24 ha, indicating a significant skew in the frequency distribution toward headwater catchments (Figure 4a). Catchment area originates mostly from the headwater subcatchments of the greater Bedload catchment.

[18] We also evaluated the relative distributions of hillslope and riparian areas (local riparian to hillslope area ratios). Headwater catchments often have smaller riparian zone percentages than larger catchments due to the relationship between riparian width and catchment scale (Figure 3b). Despite this seemingly intuitive and simple finding, channel network structure can then exert an influence on riparian-zone percentage. For example, a 3 ha catchment can be

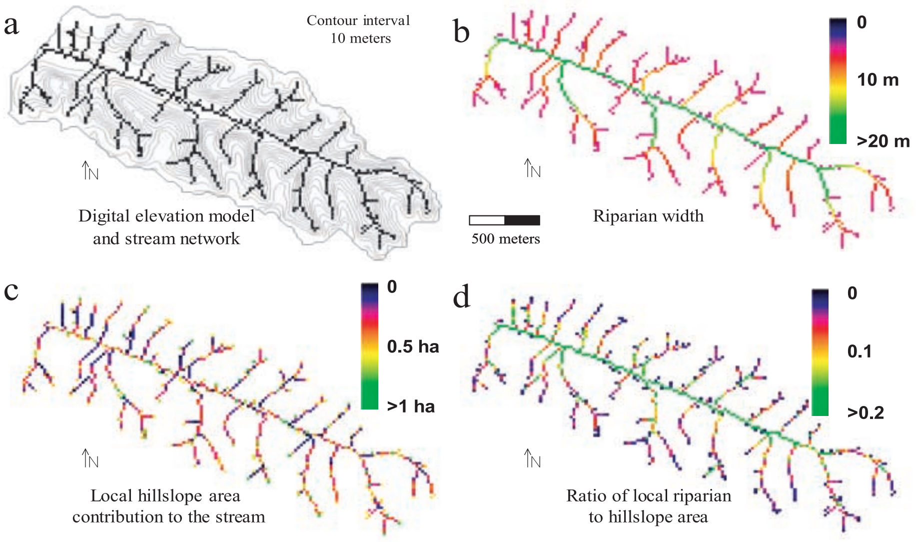

Figure 3. (a) Digital elevation model of the 280 ha Maimai catchment with the computed channel network. (b) Riparian width for each 20 m stream cell throughout the channel network. Local riparian area is equal to the riparian width times the cell length (20 m) (for histogram, see Figure 4b). (c) Hillslope area entering the channel network at each 20 m stream cell (see Figure 4c). (d) Local riparian to hillslope area ratios for each 20 m reach along the channel network (see Figure 4d).

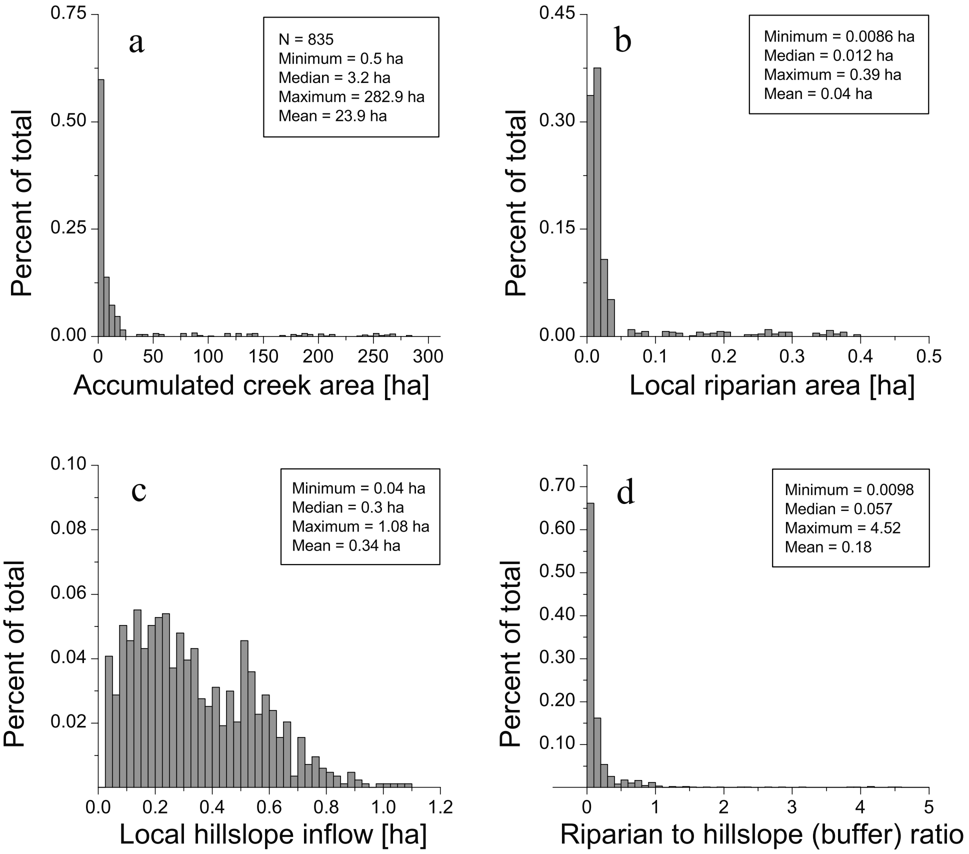

Figure 4. Histograms of calculated variables. (a) Accumulated catchment area (sum of the hillslope and riparian CDFs in Figure 5) (b) Local riparian area along the stream network for all 20 m cell stream reaches (for spatial representation see Figure 3b). (c) Local hillslope area entering the stream network for all 20 m cell stream reaches (see Figure 3c). (d) Ratio of local riparian area to local hillslope area for each 20 m cell stream reach along the channel network (see Figure 3d).

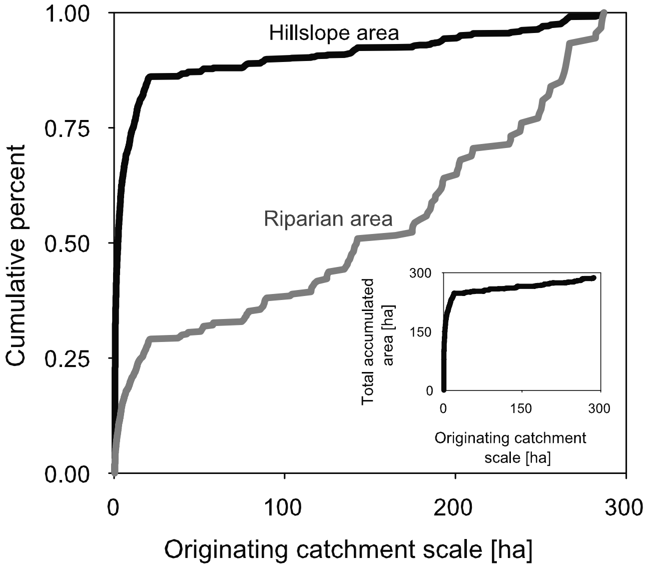

Figure 5. Cumulative percent of hillslope and riparian area versus originating catchment scale. Total catchment area is 280 ha, total hillslope area is 245 ha, and total riparian area is 35 ha. The inset plot represents total accumulated area versus originating catchment scale.

comprised of two 1.5 ha catchments that merge just prior to the 3 ha outlet and have no channel cells with accumulated area between 1.5 and 2.96 ha. This would result in a lower riparian zone percentage of catchment area than a catchment characterized by the diffuse and more linear accumulation of catchment area along one primary channel with no significant tributaries. Therefore network structure can exert an influence on riparian-zone percentage and thus riparian areal fraction relative to the lateral hillslope area. The histogram of local riparian area size along each stream cell (Figure 4b) shows the skewed frequency distribution of riparian areas toward narrow headwater riparian zones.

[19] We found a clear dissimilarity between where most upland area is accumulated and where most riparian area is accumulated. Most hillslope area is focused through narrow riparian zones, as shown in Figure 5, where near the origin of the figure, hillslope area is accumulated rapidly in sub-2.5 ha headwaters where riparian area is minimal. Riparian area is concentrated toward lower reaches of larger catchment scales, where the catchment valley bottom widens (Figure 5). 50% of the total riparian area is concentrated along the main stem of the stream network at catchment scales >140 ha. 75% of the total hillslope area is located in sub-13 ha catchments in comparison to the opposite distribution of riparian area where 75% is located in catchments >14 ha. In other words, 75% of the hillslope area is associated with 25% of the riparian zone area and 25% of the hillslope area is associated with 75% of the riparian zone area (Figure 5). This is an important observation since the capacity of the riparian zone to modulate (buffer) hillslope inputs depends on the connection of hillslopes to riparian zones [*Devito et al.*, 1996] and the inherent biogeochemical function of the riparian zone is influenced by the riparian zone position in the landscape [*Hill*, 2000].

[20] The majority (60%) of the Bedload catchment area is comprised of sub-5 ha catchments where riparian to hillslope area ratios are small (typically 0.01 to 0.12) (Figures 3 and 5). When the Bedload catchment total riparian area is divided by total hillslope area, the ratio is larger (0.14). However, this number is misleading because the local setting controls riparian area function [*Winter*, 1992; *Devito et al.*, 1996; *Hill*, 1996, 2000]. The distributed riparian to hillslope ratio (Figures 3d and 4d) has a median of 0.057 and is strongly skewed toward small riparian to hillslope ratios found predominantly in <5 ha subcatchments. The distributed map of riparian to hillslope area ratios (R/H) (Figure 3d), the associated histogram (Figure 4d), and the CDFs of riparian and hillslope area accumulation (Figure 5) each describe the dominant riparian zone setting at Maimai. Hillslope area is funneled largely through narrow headwater riparian zones and large valley bottom floodplain riparian zones are disconnected from the majority of upland areas.

[21] The ratio between riparian and hillslope area can be interpreted as a buffer capacity index. However, it is important to consider additional variables such as event magnitude, duration, and frequency, as well as antecedent conditions, when examining riparian zone function during storm events. Furthermore, variations in soil depth might be of importance [*Devito et al.*, 1996] as the volume of the riparian zone relative to the volume of the hillslope zone could be more important than area in catchments with greater soil depth variability.

5. Concluding Remarks

[22] The technique outlined in this paper reveals information from digital elevation models not exposed previously. The pieces that form each step in this analysis are simple. Combined, stream reach to stream reach riparian assessment is possible using the information contained in a DEM (using a simple program available from the authors). We found that headwater riparian areas were narrower, but more tightly connected to hillslope inputs. The obvious implication is that overall catchment riparian buffering capacity is determined in headwater riparian zones. Larger catchment scale valley bottoms were disconnected from where the bulk of hillslope inputs originate. The implication is that wider valley bottom floodplains have low potential to buffer hillslope runoff. Combined, the maps and distributions of hillslope and riparian area inputs to the stream network provide a distributed riparian to hillslope area measure and a distributed estimation of potential riparian buffer capacities. Each of the different coverages provides information on the hydrological conditions within a catchment. The topographical analyses described in this paper might also useful for geomorphologic analysis, especially since the importance of stream network organization is increasingly recognized [*Brown and Quine*, 1999; *Richards*, 1999]. The ratio between local riparian and hillslope areas, for instance, might distinguish areas of predominant erosion or deposition. The distributions of the different indices might also be useful for comparison of different catchments or landscapes and as a tool to increase efficiency of management scenarios.

[23] **Acknowledgments.** We extend our thanks to John Payne, Jagath Ekanayake, and Breck Bowden of LandCare Research, NZ for logistical, technical, and collaborative support and to Robert S. McGlynn for invaluable assistance in the field. We also thank Jeff McDonnell, Rick Hooper, Carol Kendall, and Jamie Shanley for useful comments. This work

was made possible by NSF grant EAR-0196381 and the 2001 AGU Horton Research Grant awarded to BLM as well as funding from the Swedish Research Council (grant 620-20001065/2001) to JS. This manuscript has been assigned Journal Series 2002-62, Montana Agricultural Experiment Station, Montana State University-Bozeman.

References

Anderson, M. G., and T. P. Burt, The role of topography in controlling throughflow generation, *Earth Surf. Processes Landforms*, *3*, 331–334, 1978.

Bates, P. D., M. D. Stewart, A. Desitter, M. G. Anderson, J. P. Renaud, and J. A. Smith, Numerical simulation of floodplain hydrology, *Water Resour. Res.*, *36*, 2517–2529, 2000.

Beven, K. J., The hydrological response of headwater and sideslope areas, *Hydrol. Sci. Bull.*, *23*, 419–437, 1978.

Beven, K. J., and M. J. Kirkby, A physically based, variable contributing area model of basin hydrology, *Hydrol. Sci. Bull.*, *24*, 43–69, 1979.

Blavet, D., E. Matheb, and J. C. Lepruna, Relations between soil colour and waterlogging duration in a representative hillside of the West African granito-gneissic bedrock, *Catena*, *39*, 187–210, 2000.

Brinson, M. M., Changes in the functioning of wetlands along environmental gradients, *Wetlands*, *13*, 65–74, 1993.

Brinson, M. M., B. L. Swift, R. C. Plantico, and J. S. Barclay, Riparian ecosystems: Their ecology and status, *U.S. FWS/OBS-81/17*, Fish and Wildlife Serv., Biol. Serv. Program, Washington, D. C., 1981.

Brown, A. G., and T. A. Quine (Eds.), *Fluvial Processes and Environmental Change*, John Wiley, New York, 1999.

Burns, D. A., J. J. McDonnell, R. P. Hooper, N. E. Peters, J. E. Freer, C. Kendall, and K. Beven, Quantifying contributions to storm runoff through end-member mixing analysis and hydrologic measurements at the Panola Mountain Research Watershed (Georgia, USA), *Hydrol. Processes*, *15*, 1903–1924, 2001.

Cirmo, C. P., and J. J. McDonnell, Linking the hydrologic and biochemical controls of nitrogen transport in near-stream zones of temperate-forested catchments: A review, *J. Hydrol.*, *199*, 88–120, 1997.

Devito, K., Sulphate mass balances of Precambrian shield wetlands: The influence of catchment hydrogeology, *Can. J. Fish. Aquat. Sci.*, *52*, 1750–1760, 1995.

Devito, K. J., A. R. Hill, and N. Roulet, Groundwater-surface water interactions in headwater forested wetlands of the Canadian Shield, *J. Hydrol.*, *181*, 127–147, 1996.

Dietrich, W. E., and T. Dunne, The channel head, in *Channel Network Hydrology*, edited by K. Beven and M. Kirkby, pp. 175–220, John Wiley, New York, 1993.

Dunne, T., Field studies of hillslope flow processes, in *Hillslope Hydrology*, edited by M. J. Kirkby, pp. 227–293, John Wiley, New York, 1978.

Freeze, A. R., Role of subsurface flow in generating surface runoff: 2. Upstream source areas, *Water Resour. Res.*, *8*, 1272–1283, 1972.

Gregory, K. J., and D. E. Walling, *Drainage Basin Form and Process: A Geomorphological Approach*, Edward Arnold, London, 1973.

Hewlett, J. D., and A. R. Hibbert, Factors affecting the response of small watersheds to precipitation in humid areas, in *Forest Hydrology*, edited by W. E. Sopper and H. W. Lull, pp. 275–290, Pergamon, New York, 1967.

Hill, A. R., Ground water flow paths in relation to nitrogen chemistry in the near-stream zone, *Hydrobiologia*, *206*, 39–52, 1990.

Hill, A. R., Nitrate removal in stream riparian zones, *J. Environ. Qual.*, *25*, 743–755, 1996.

Hill, A. R., Stream chemistry and riparian zones, in *Streams and Ground Waters*, pp. 83–110, Academic, San Diego, Calif., 2000.

Hooper, R., B. Aulenbach, D. Burns, J. J. McDonnell, J. Freer, C. Kendall, and K. Beven, Riparian control of streamwater chemistry: Implications for hydrochemical basin models, *IAHS Publ.*, *248*, 451–458, 1997.

Leopold, L. B., M. G. Wolman, and J. P. Miller, *Fluvial Processes in Geomorphology*, Dover, Mineola, N. Y., 1992.

Lowrance, R. R., R. Leonard, and J. Sheriden, Managing riparian ecosystem to control nonpoint source pollution, *J. Soil Water Conserv.*, *40*, 87–91, 1985.

McGlynn, B. L., and J. J. McDonnell, Role of discrete landscape units in controlling catchment dissolved organic carbon dynamics, *Water Resour. Res*, *39*, doi:10.1029/2002WR001525, in press, 2003.

McGlynn, B. L., J. J. McDonnell, J. B. Shanley, and C. Kendall, Riparian zone flowpath dynamics during snowmelt in a small headwater catchment, *J. Hydrol.*, *222*, 75–92, 1999.

McGlynn, B. L., J. J. McDonnell, and D. D. Brammer, A review of the evolving perceptual model of hillslope flowpaths at the Maimai catchments, New Zealand, *J. Hydrol.*, *257*, 1–26, 2002.

Megonigal, J. P., W. H. Patrick, and S. P. Faulkner, Wetland identification in seasonally flooded forest soils: Soil morphology and redox dynamics, *Soil Sci. Soc. Am.J.*, *57*, 140–149, 1993.

Merot, P., B. Ezzahar, C. Walter, and P. Aurousseau, Mapping waterlogging of soils using digital terrain models, *Hydrol. Processes*, *9*, 27–34, 1995.

Mew, G., T. H. Webb, C. W. Ross, and J. Adams, Soils of the Inangahua Depression, South Island, New Zealand, N. Z. Soil Surv., Christchurch, 1975.

Mitsch, W. J., and J. G. Gosselink, *Wetlands*, 2nd ed., Van Nostrand Reinhold, New York, 1993.

Mosley, M. P., Streamflow generation in a forested watershed, New Zealand, *Water Resour. Res.*, *15*, 795–806, 1979.

Mosley, M. P., Subsurface flow velocities through selected forest soils, South Island, New Zealand, *J. Hydrol.*, *55*, 65–92, 1982.

Pearce, A. J., M. K. Stewart, and M. G. Sklash, Storm runoff generation in humid headwater catchments: 1. Where does the water come from?, *Water Resour. Res.*, *22*, 1263–1272, 1986.

Phillips, D. H., J. E. Fossa, C. A. Stilesa, C. C. Trettinb, and R. J. Luxmoore, Soil-landscape relationships at the lower reaches of a watershed at Bear Creek near Oak Ridge, Tennessee, *Catena*, *44*, 205–222, 2001.

Quinn, P. F., K. J. Beven, and R. Lamb, The ln(a/tanβ) index: How to calculate it and how to use it within the TOPMODEL framework, *Hydrol. Processes*, *9*, 161–182, 1995.

Richards, K., The magnitude-frequency concept in fluvial geomorphology: A component of a degenerating research programme?, *Z. Geomorphol., Suppl. B*, *115*, 1–18, 1999.

Tarboton, D. G., A new method for the determination of flow directions and upslope areas in grid digital elevation models, *Water Resour. Res.*, *33*, 309–319, 1997.

Weyman, D. R., Throughflow on hillslopes and its relation to the stream hydrograph, *Bull. Int. Assoc. Sci. Hydrol.*, *15*, 25–33, 1970.

Winter, T. C., A physiographic and climatic framework for hydrologic studies of wetlands, in *Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource Management*, *NHRI Symp. Ser. 7*, edited by R. D. Robarts and M. L. Bothwell, pp. 127–148, Environ. Can., Saskatoon, Saskatchewan, 1992.

Wondzell, S. M., Flux of groundwater and nitrogen through the floodplain of a fourth-order stream, Ph.D. dissertation, Oreg. State Univ., Corvallis, 1994.

Woods, R. A., and M. Sivapalan, A connection between topographically driven runoff generation and channel network structure, *Water Resour. Res.*, *33*, 2939–2950, 1997.

Zhang, W., and D. R. Montgomery, Digital elevation model grid size, landscape representation, and hydrologic simulations, *Water Resour. Res.*, *30*, 1019–1028, 1994.

B. L. McGlynn, Department of Land Resources and Environmental Sciences, Montana State University, 334 Leon Johnson Hall, P.O. Box 173120, Bozeman, MT 59717-3120, USA. (bmcglynn@montana.edu)

J. Seibert, Department of Environmental Assessment, Swedish University of Agricultural Sciences (SLU), Box 7050, SE-75007 Uppsala, Sweden. (jan.seibert@ma.slu.se)