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Evaluating sediment sources and delivery in a tropical volcanic watershed

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Abstract This paper presents the results of a two-year integrated study that considered the relationship between erosion and river sediment yield in a volcanic upland river catchment in Indonesia. Sediment yield was measured in three subcatchments, as well as in the main catchment. In addition, all possible sources of sediment were quantified and compared with the river sediment yield. Rainfed agricultural land contributed nearly half of the soil erosion, on average, while hillside trails, settlements and roads, and non-surface erosion contributed the rest. The high sediment delivery ratios (>100%) suggest an efficient sediment transport mechanism, even in the lower parts of the main catchment and subcatchments. Often, sediment budget evaluations compare only measured (suspended) sediment yields with estimated erosion values for agricultural land. However, the results of this study make it clear that all components of the balance should be included.

Key words humid tropics; sediment delivery ratio; sediment yield; soil erosion

INTRODUCTION

The high sediment loads of Java’s rivers are considered a serious problem and, since the beginning of the 19th century, various soil conservation programmes, mainly aimed at agriculture, have been implemented. Although most upland agricultural land is now bench-terraced, the problem persists and the effectiveness of these programmes has been challenged. For example, Diemont *et al.* (1991) point out that although rainfed agriculture is an important sediment source, it is not the only cause of high sedimentation rates in Java’s rivers. Those authors suggested that geological morpho-erosion and accelerated morpho-erosion (such as accelerated hillslope retreat resulting from the expansion of irrigated ricefields) also play an important role, as do built-up areas and volcanic eruptions. Erosion studies concerning agricultural practices and their socio-economic context in Indonesia are common (e.g. Purwanto, 1999; Van Dijk, 2002). Detailed studies on other possible sediment contributors, such as roads and trails (Rijsdijk *et al.*, 2004a), and gullies and landslides (Rijsdijk *et al.*, 2004b), have also been published recently. Comprehensive sediment-budget studies on different scales in the humid tropics are much less frequent, although notable exceptions include those of Amphlett (1988) in the Philippines, Balamurugan (1991) in Malaysia and Turkelboom (1999) in Thailand.

The comprehensive study described here was conducted within the framework of the Konto River Project, a joint, multidisciplinary project implemented by the governments of The Netherlands and Indonesia. The project aimed to develop a

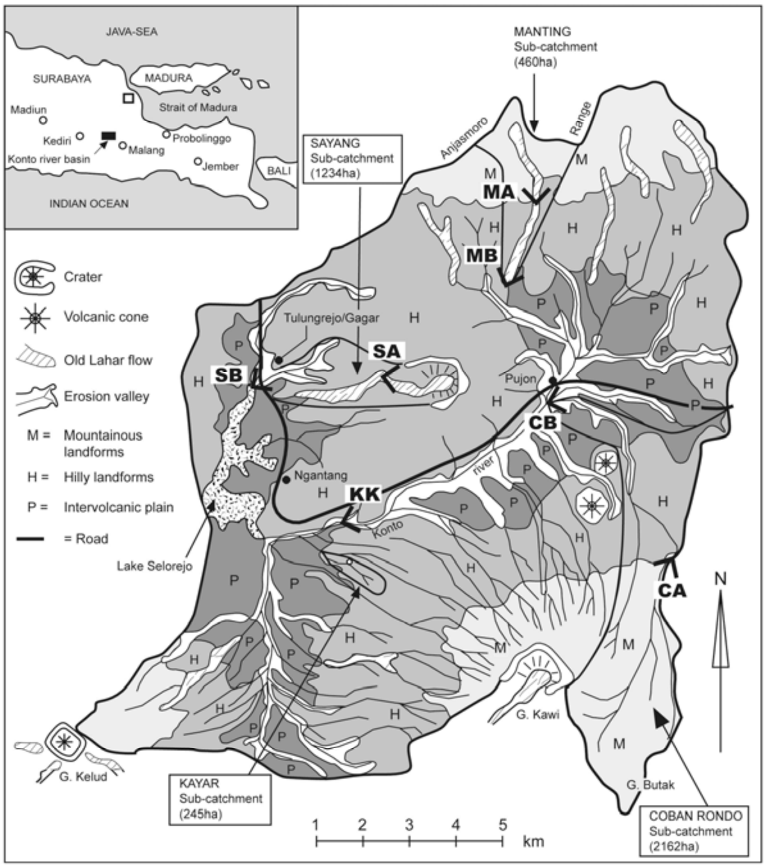

Fig. 1 Location and general geomorphology of the Upper Konto catchment, East Java (after Nuffic-Unibraw, 1984), with locations of study sites added.

planning procedure to establish a management model for Java's densely populated watersheds (Anon., 1989). The main erosion research activities were carried out from 1987 until the end of the project in 1990. Presented here is an extrapolation, to catchment scale, of data on individual sediment sources measured within the project (vegetated surfaces, trails, gullies, landslides, ricefield-terrace collapse, accelerated hillslope retreat and riverbank erosion), and a comparison of these data with river sediment yields.

DESCRIPTION OF THE STUDY CATCHMENTS

Indonesia's upper Konto River catchment (part of the large Brantas River system) is about 25 km northwest of the East Javan town of Malang. The Konto drains a young volcanic watershed (233 km^2; Fig. 1) and flows into an artificial lake (Lake Selorejo). The catchment comprises intervolcanic plains and plateaux (25%), alluvial and lahar valleys (5%), hilly areas (50%) and volcanic mountain complexes (20%). Within the upper Konto catchment, three subcatchments were studied in detail: Coban Rondo (2162 ha), Manting (460 ha) and Sayang (1234 ha), together accounting for 17% of the total catchment area (Fig. 1). The soils in the upper Konto area are classified (FAO, 1990) as Andosols (on mountainous landforms), Cambisols (on lower slopes and foothills), and Luvisols (on lower plains where irrigated rice cultivation is practised) (NUFFIC-UNIBRAW, 1984). The climate is typical of higher elevations in a tropical monsoon climate, with quite pronounced wet and dry seasons (Oldeman, 1975). Long-term rainfall averages range from 2700 mm in the southwest to 2125 mm in the northeast (P.U. Brantas, 2001). In 1988, 1989 and 1990 the mean areal rainfall was 2162, 2618 and 3443 mm respectively (Rijsdijk & Bruijnzeel, 1990).

The steep area above 1400 m is covered with (degraded) natural forest, mature tree plantations, shrubland and, at altitudes of 1200–1400 m, "agroforestry" (intercropping of food crops and young timber trees) is found. The main land uses in the lowest parts of the catchment are: intensive rainfed agriculture (maize and cassava, on well-maintained forward-sloping terraces); irrigated rice cultivation; bamboo plantations; homegardens containing coffee under shade trees; and settlements (houses and yards, village roads, and stables) (RIN, 1985). Settlements are connected by cobblestone or dirt roads in various states of repair: around 50% can be classified as well-maintained and 50% as poorly maintained. All vegetated areas are intersected by numerous small trails, both consolidated and unconsolidated. In each land-use type, the percentage of the total land area accounted for by consolidated and unconsolidated trails respectively, was estimated during field surveys to be 0.75% and 0.75% in forest; 1% and 0.25% in plantation forest; 0.5% and 0.25% in shrubland; 0% and 3% in agroforestry; 1% and 1% in rainfed agriculture; 1.5% and 1.5% in bamboo; and 2.5% and 0.5% in coffee and mixed gardens. Gullies and landslides are relatively rare in the Konto upper watershed, except in the Kayar basin (Rijsdijk *et al*., 2004b) and along the road from Pujon to Ngangtang (Rijsdijk *et al*., 2004a; Fig. 1).

MEASUREMENT PROCEDURES

In 1988 and 1989, the daily sediment yields of the main vegetated areas were measured in the Coban Rondo and Sayang subcatchments using Wischmeier type erosion plots (Wischmeier & Smith, 1978). The sediment yields of trails and country roads were measured in the Coban Rondo and the Sayang subcatchments in 1989, and converted to annual values (presented below) using a regression-based procedure (Rijsdijk *et al.*, 2004a). The same method was used to estimate sediment production by gullies in the Coban Rondo subcatchment (Rijsdijk *et al.*, 2004b). In 1990, the volumes of landslides along the main road through the Konto upper watershed were monitored (Rijsdijk *et al.*, 2004a), and in 2001 estimates were made of the volume of sediment produced by the collapse of the lowest irrigated rice terraces in the Sayang and Coban Rondo subcatchments. Also in 2001, the accelerated hillslope retreat caused by farmers enlarging the area of their ricefields was quantified (Rijsdijk *et al.*, 2004b). In 1989 the rate of denudation of riverbanks was quantified by: (a) measuring bank retreat using erosion pins, and (b) comparing the grain size distribution of the bed load with that of the riverbank material (Rijsdijk, unpublished study).

During 1988 and 1989, river sediment load (suspended load and bed load) was measured at two locations within each of the Coban Rondo, Manting and Sayang subcatchments: the upper ("A") gauging stations (CA, MA and SA) were located just below the (relatively) undisturbed parts of the subcatchments; the lower ("B") stations

(CB, MB and SB) were located at the outflow of each subcatchment (Fig. 1). Suspended sediment load was determined daily, using the event based method (EBM; Guy & Norman, 1970). The EBM (which is considered a more accurate method) could give results which are one-third higher than those obtained using the conventional sediment rating curve–flow duration method (SRC–FDM) (Rijsdijk & Bruijnzeel, 1990).

The suspended sediment yield of the Konto River, at the Kambal station (KK, Fig. 1) itself was measured in 1990 using the SRC–FDM. Bed load was measured using large slot traps in the river bed at all stations except in the Konto River (where it was estimated) (Rijsdijk & Bruijnzeel, 1990). All sediment sources quantified were then used to calculate sediment delivery ratios (SDRs; off-site sediment yield/on-site erosion) for all subcatchments and the entire Konto catchment.

RESULTS

In 1988 and 1989, respectively, sediment yields (Mg ha^{-1} $year^{-1}$) were 0.14 and 0.17 for agroforestry (in Coban Rondo); 0.71 and 0.60 for coffee gardens in Coban Rondo, and 1.1 and 1.0 for coffee gardens in Sayang; 25 and 52 for rainfed agriculture in Coban Rondo and 9.4 and 41 for rainfed agriculture in Sayang. However, the very low value obtained for rainfed agriculture in Sayang in 1988 was not considered representative, and was thus replaced by the value for Coban Rondo (Rijsdijk & Bruijnzeel, 1990). In both years, the sediment production of (disturbed) natural forest and shrubland was negligible. The sediment yields of plantation forest and bamboo were assumed to be similar to those of coffee gardens, as total biomass, understorey vegetation and litter cover were similar for each of these land-cover types.

Stable, consolidated trails with overgrown shoulders or risers produced 65 Mg ha^{-1} and 75 Mg ha^{-1} of sediment annually in 1988 and 1989, respectively. By contrast, unconsolidated trails, with much loose soil, yielded 433 and 411 Mg ha^{-1} (Rijsdijk *et al.*, 2004a). In the same years, in Coban Rondo, a poorly maintained cobblestone road yielded 65 and 73 Mg ha^{-1} respectively, and a well-maintained road 18 and 20 Mg ha^{-1}. The sediment yield of settlements was estimated to be 35 and 40 Mg ha^{-1} for 1988 and 1989 respectively, using measurements made of roads and trails inside villages (Rijsdijk *et al.*, 2004a).

In 2001, the annual contribution of terrace and bank collapse along the Coban Rondo and Sayang Rivers was estimated to be 109 Mg and 566 Mg, respectively. A comparison of rainfall totals for the respective years (~2400 mm in 2001 *vs* ~2162 mm in 1988 and 2618 mm in 1989) suggests that the 2001 estimates are comparable with those of 1988 and 1989. Gully erosion as measured in the Coban Rondo catchment yielded 22 Mg ha^{-1} in 1989 (Rijsdijk *et al.*, 2004b). Accelerated hillside retreat amounted to 150 Mg $year^{-1}$ in the Sayang subcatchment (Rijsdijk, personal observation). Sediment output (suspended load and bed load) for 1988 and 1989 at all the river gauging stations are presented in Table 1. The same table also presents the relative contribution of all the above sediment sources in the three selected subcatchments and the entire Konto catchment (see also Figs 2 and 3), along with the SDRs calculated for each area.

Table 1 Erosion and sediment yield data for the research basins.

Unit	Upper Sayang			Lower Sayang			Upper Coban Rondo			Lower Coban Rondo		
	Surface (ha)	Erosion (Mg) 1988	1989	Surface (ha)	Erosion (Mg) 1988	1989	Surface (ha)	Erosion (Mg) 1988	1989	Surface (Ha)	Erosion (Mg) 1988	1989
Natural forest	203	0	0	401	0	0	1031	0	0	1036	0	0
Plantation forest	57	63	57	148	164	149	3	2	2	135	96	81
Agroforestry	10	1	2	12	2	2	0	0	0	85	12	14
Shrub	62	0	0	278	0	0	133	0	0	144	0	0
Bamboo	0	0	0	7	8	7	0	0	0	50	36	30
Coffee garden	1	1	1	52	57	52	0	0	0	9	6	5
Rainfed agricult.	4	100	164	95	2375	3895	0	0	0	310	7750	16120
Irrig. rice fields	0	0	0	138	0	0	0	0	0	164	0	0
Riverbank slides	0	0	0	4	566	566	0	0	0	4	109	109
Hillslope retreat	0	0	0	1	150	150	0	0	0	0	0	0
Unconsolid. trails	1.0	415	393	3.2	1380	1310	1	277	263	8	3322	3153
Consolid. trails	1.6	105	121	14.2	924	1066	1	64	74	37	2382	2748
Settlements	0	0	0	30	1050	1200	0	0	0	138	4830	5520
Roads	0	0	0	25	1050	1175	0	0	0	20	840	940
Channel scouring	0.05	495	436	4	2590	2738	2	32	14	3	3502	5052
Gullies	0	0	0	22	440	440	0	0	0	20	440	440
Total (Mg)	340*	1180	1175	1234*	10756	12750	1170*	375	353	2162*	23325	34214
Total (Mg ha^{-1})		3.5	3.5		8.7	10.4		0.3	0.3		10.8	15.8
Sediment yield (Mg ha^{-1})		3.9	3.8		12.1	11.2		0.2	0.5		5.8	14.1
SDR		1.1	1.1		1.4	1.1		1.5	0.8		0.5	0.9

DISCUSSION AND CONCLUSIONS

The results (summarized in Table 1) show that, although rainfed agriculture is an important source of sediment, non-vegetated surfaces such as channels, trails, roads and settlements are equally important. Ricefields may be an insignificant sediment contributor; but they can cause many small-scale landslides along the river channels. Although the sediment yields of agroforestry fields are actually rather low, the current trend of converting shrubland to agroforestry is likely to increase sediment yields overall, because the number of unconsolidated trails through these fields will increase. Increased population pressure may also increase sediment yields, as the density of trails and roads (which are more vulnerable to erosion) would increase. In addition, more impermeable surfaces would increase quickflow in rivers (Rijsdijk *et al.*, 2004b) which could result in greater channel scouring. However, more settlements would not mean higher sediment yields, as settlements do not have higher erosion rates than agricultural land.

The high SDRs indicate efficient removal of sediment. This is plausible in view of the deeply incised channels of the Konto catchment, which lack the space required for deposition. The highest SDRs were found in the relatively undisturbed, steep head-water areas, where there is even less space for sediment to be deposited. Since the sediment production of the densely vegetated forests and shrubland in the upper catchments is virtually zero, all river sediment not accounted for must originate from

Table 1 (continued) Erosion and sediment yield data for the research basins.

	Upper Manting[a]			Lower Manting[a]			Konto subcatchment[b]	
Unit	Surface (ha)	Erosion (Mg)		Surface (ha)	Erosion (Mg)		Surface (ha)	Erosion (Mg)
		1988	1989		1988	1989		Average
Natural forest	317	0	0	317	0	0	5800	0
Plantation forest	4	3	2	25	18	15	1200	1080
Agroforestry	1	0	0	32	4	5	750	120
Shrub	65	0	0	83	0	0	7000	0
Bamboo	0	0	0	0	0	0	400	360
Coffee garden	0	0	0	0	0	0	700	630
Rainfed agricult.	0	0	0	0	0	0	3500	137550
Irrig. rice fields	0	0	0	0	0	0	2000	0
Riverbank slides	0	0	0	0	0	0	30	2750
Hillslope retreat	0	0	0	0	0	0	1	300
Unconsolid. trails	0.3	118	112	1	551	522	90	37800
Consolid. trails	0.4	29	33	0	49	57	433	30310
Settlements	0	0	0	0	0	0	800	30400
Roads	0	0	0	2	84	92	300	13500
Channel scouring	0.01	4	3	0.02	34	37	1	23000
Gullies	0	0	0	0	0	0	245	12250
Total (Mg)	387[*]	154	151	460[*]	740	728	23300[*]	291150
Total (Mg ha^{-1})		0.4	0.4		1.6	1.5		12
Sediment yield (Mg ha^{-1})		0.8	1.1		0.9	1.3		11–16
SDR		1.9	2.8		0.5	0.9		0.9–1.3

[a] Surface erosion rates from measurements in the Coban Rondo subcatchment.

[b] Average erosion rates from the Coban rondo and Sayang subcatchments.

[*] Ha

small tributary streams or hidden landslides. But also the values for the lower stations (Sayang), are remarkably high. Besides extrapolation errors, overlooked sediment sources could include slides of complete terraces (which was observed once in 1990), or scour caused by the small channels which drain water from the terraces to the river. Of particular interest is the difference between the SDRs recorded at the MA and MB stations (1.9 *vs* 0.8 in 1988, and 2.8 *vs* 0.5 in 1989). This can be explained by the fact that the extra sediment resulting from the creation of new agroforestry fields in 1988, in the area between stations MA and MB, had not yet reached the river and could not contribute to the river sediment yield.

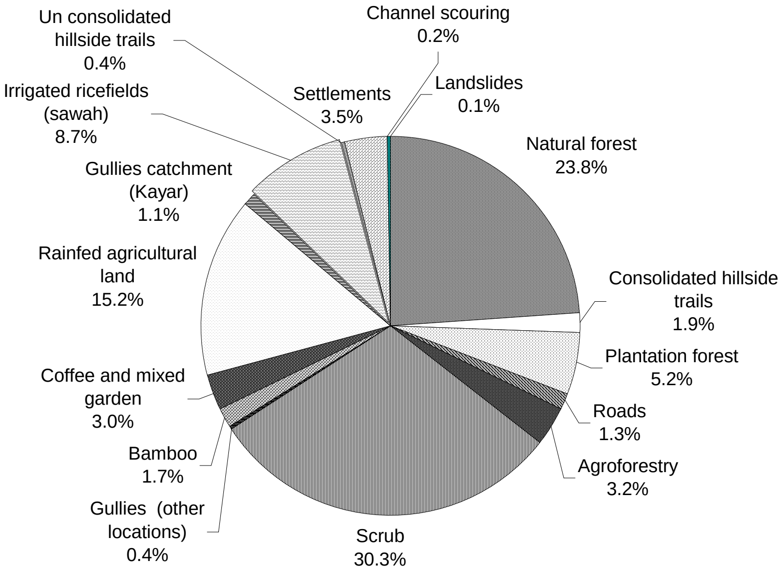

Fig. 2 Land use in the Konto River catchment.

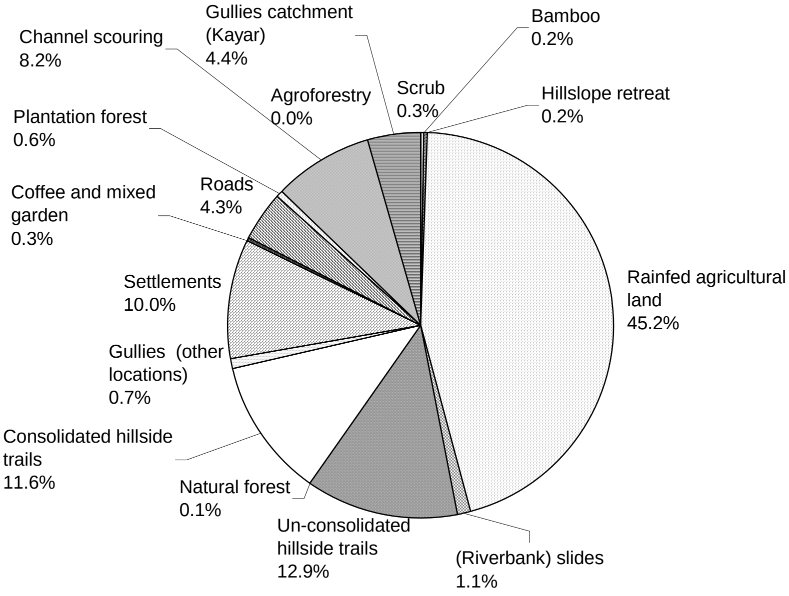

Fig. 3 Sediment sources in the Upper Konto catchment.

Despite the large error margins which can result from upscaling (Böhm, 1998), the relatively short measurement period (Campbell, 1992) and because of the influence of extreme events (Amphlett, 1988), the average sediment yields of the three basins (Table 1) are consistent with the estimated siltation rates of Lake Selorejo of 11–16 Mg ha^{-1} year^{-1} (Fisch, 1983; P.U. Brantas, 1989), if account is taken of the yield of the Kayar subcatchment (50 Mg ha^{-1}; Rijsdijk *et al.*, 2004b) and of the high yields of the Konto River (22 Mg ha^{-1}, measured at station KK; Fig 1) during an extremely wet year (1990: 3433 mm rainfall) in which there were many landslides (contributing 2600 Mg; Rijsdijk *et al.*, 2004b). The SDR of the entire Konto catchment (0.9–1.3) did not indicate a decrease in SDR with an increase in scale as some investigators have found (e.g. Gong & Xiong, 1980). This, however, is plausible in view of the lack of channel storage.

Although, the average values of SDR for the lower stations in Coban Rondo (0.7) and Manting (0.7) are in line with the values of 0.4–0.7 reported by Purwanto (1999) for a 105-ha catchment in Central Java, it is difficult, to compare these results with the work of others. For example, the Event Based Method, as applied in this study to measure the river sediment yield, results in higher (and more accurate) values for suspended sediment load than the conventional Flow Duration Curve method. The erosion rates of vegetated surfaces, as well as the bed load component of the sediment loads of the rivers, have been measured not estimated, as is often the case, and, most important, this study shows that all possible sediment sources have to be included to obtain a reliable view of catchments erosion rates.

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Lake-catchments: an evaluation of their contribution to studies of sediment yield and delivery processes. Ian D. L. foster, john a. bearing & robert grew. Department of Geography, Coventry Polytechnic, Priory Street, Coventry CV1 5FB, UK.Â Sediment sources and budgeting. Catchment based studies of contemporary (Rapp, 1960) and historical (Trimble, 1976) sediment source area/yield relationships add a significant dimension to the understanding and prediction of sediment yields through the sediment budgeting approach.Â C, Magnetic susceptibility, HIRM and the HIRM: susceptibility ratio in a sediment core from Dayat er Roumi (North Africa) showing gully initiation (a), downcutting (b), widening (c) and stabilization (d) (Foster et al, 1986). Evaluating SWAT Model Performance for Runoff, Percolation, and Sediment Loss Estimation in Low-Gradient Watersheds of the Atlantic Coastal Plain. by. Kerry L. Mapes.Â An additional eight tropical storms also made landfall in southeastern North Carolina during that time period [37]. The geology is primarily sedimentary rock and unconsolidated sediments.Â In SWAT, sediment yield at each sub-watershed outlet is quantified in the OUTPUT.RCH file (SED_OUT.rch), while sediment delivery to streams is better approximated using SYLD.sub, which is in the OUTPUT.SUB file. SYLD.sub is a measurement of sediment from the sub-watershed that is transported to the reach during a given time-step and is referred to here as sediment loss. Nutrient and sediment pollution affects many of our local streams and lakes, and can lead to adverse impacts such as algal blooms, fish kills, and dead zones. Given the growing importance of managing nutrient and sediment pollution there is interest in tools that can help estimate and track nutrient losses as well as provide decision support for policy or investment options. The purpose of this document is to identify and catalog many of the tools that are currently in use to estimate nitrogen, phosphorus, and sediment losses and to identify the uses for which these tools are most appropriate.Â An in-stream routing and sediment transport component in BasinSIM 1.0 employs the algorithms in AnnAGNPS to simulate sediment transport. MapShed. In recently active volcanic areas in tropical regions, caldera lakes1 are important water systems that supply water, habitat for fish and other aquatic resources, and a venue for outdoor recreation and tourism.Â Such components for tropical settings in a caldera watershed are precipitation, evapotranspiration, evaporation, surface water, ground-water flow, changes in storage (surface waterâ€"groundwater) and human interactions such as inputs and withdrawals.Â Nonpoint sources around Calderas watershed are diffuse, distributed over land and discharged to calderaâ€™s lake by surface runoff, agricultural activities and other diffuse pollution such as sediment loading or solid waste transport.