Annual Sediment and Nutrient Contribution from Two Tropical Subbasins

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SUMMARY

Concentrations and annual discharges of suspended sediments (SS), total phosphorus (TP), dissolved phosphorus (DP), and total Kjeldhal nitrogen (TKN) were quantified during runoff events (storm) in two rural subbasins of contrasting landuse; Miraflores (area of 224 ha) and Cerro Gordo (715 ha), in western Puerto Rico. Average concentration values for SS, TP, DP, and TKN were 1,154 and 2,018 mg SS L⁻¹, 0.197 and 0.268 mg TP L⁻¹, 0.056 and 0.016 mg DP L⁻¹, and 1.07 and 1.28 mg TKN L⁻¹ for Miraflores and Cerro Gordo, respectively, in storm events ranging from 1.2 to 193 mm. Empirical constituent concentrations collected during storm events, base-flow and elevated base-flow (low-intermediate flows) combined with hydrologic modeling revealed that annual yields of SS, TP, DP and TKN (kg ha⁻¹) in the Cerro Gordo subbasin were 43,919, 4.96, 0.33, and 21.8, respectively, and 30,745, 3.89, 1.09, 16.9 in Miraflores subbasin. Over 97% of the annual nutrient and sediment contribution occurred during storm events. The change in SS and nutrient loads per runoff depth increase were similar in the two subbasins but there were greater loads at specific runoff depths in Cerro Gordo. There appear to be similar transport mechanisms in the two subbasins, but Cerro Gordo has greater background concentrations possibly as a result of more intensive agricultural activities.

INTRODUCTION

Three of the most important contaminants in surface waters related to non-point sources are suspended sediments (SS), nitrogen (N) and phosphorus (P) (USEPA, 1986). Contributing non-point sources are agricultural activities, unsewered urban and suburban areas, landfills, and construction sites. Elevated nutrients impair downstream water quality by promoting eutrophication and elevated sediment concentrations reduce both water clarity and dissolved
oxygen concentrations. Both N and P could be limiting biological productivity in tropical
surface waters (Salas and Martinó, 1991; Downing et al., 1999; Martínez et al. 2005). Water-
quality data for Puerto Rico indicate that nutrients are responsible for surface water-quality
degradation and in lake primary production responds to nutrient flushes from runoff events
(Martínez et al. 2005). Thus, quantification of nutrient export from watersheds therein are of
importance for protection and management of tropical watersheds.

Land use in Puerto Rico has been drastically altered as a result of changes in land cover
from economic growth and population change (Aide and Grau, 2004). In the 19th and early part
of the 20th century agricultural practices and land-clearing for fuel was responsible for a large
part of the hillslope erosion. During the shift from agricultural to industrial and residential land
uses over the past 50 years, rivers continue to transport sediment temporarily stored in alluvial
valleys (Warne et al., 2005). These activities have influenced both in-stream and reservoir water
quality and aquatic life. Scientific understanding of nutrient export and cycling from
anthropogenically impacted watersheds in temperate areas may not be applied in a general way
to tropical areas because of latitudinal differences in climate, nutrient cycling and hydrological
patterns (Downing et al., 1999; Lewis, 2002). It is not clear if similar patterns of sediment and
nutrient export are observed for adjacent tropical subbasins with similar hydrology but with
varying land use. In this study we describe nutrient concentrations and export during both low-
intermediate flows and storm events and quantify SS and nutrient export from two subbasins of
contrasting land use. Because nutrient concentrations and dynamics during low-intermediate
flows have been described previously (Sotomayor et al., 2005), emphasis is given in describing
sediment and nutrient concentrations and yields during storm events and in the quantification of
annual loads and yields.
MATERIALS AND METHODS

Study area description: The Rio Grande de Añasco (RGA) watershed is located in western Puerto Rico and extends over seven municipalities. It is one of the largest in Puerto Rico with a catchment area of about 48,130 ha (Diaz et al., 1998). The Añasco River is born at elevation 1,204 m and flows westward for 74 km to discharge into the Añasco/Mayagüez Bay. Possible major sources of pollution include land disposal of wastewater systems, industrial point sources, and agricultural activities (PREQB, 2002). Two subbasins (Miraflores and Cerro Gordo) of the Río Grande de Añasco watershed were studied. Miraflores and Cerro Gordo are 224 and 714 ha in area, respectively and have approximately the same aerial proportion (87 and 79%) in rangeland, pasture, and secondary forest (Table 1). Of the remaining land area, Miraflores has a lesser proportion in agriculture and a greater proportion of land under suburban use, with the inverse occurring in Cerro Gordo. The primary crops grown in the agricultural areas of the subbasins are banana and plantains (Musa spp.), coffee (Coffea arabica L.), citrus (Citrus spp.), Yam (Dioscorea spp.), and other commodities.

Data collection: Nutrient annual loads were estimated from the combination of grab samples and storm (runoff) events. Grab samples were collected from May 2003 to December 2004 and storm events were collected from August 2003 to 31 August 2004. Grab samples included water samples collected during base-flow and elevated base-flow (low-intermediate flows) (Pérez-Alegría et al., 2005; Corvera-Gomringer, 2004). At the outlet each of the two subbasins, an ISCO® 3700 automatic sampler (ISCO Corp. Lincoln NE) was installed. Surface water elevation was continuously monitored with the ISCO® 4200 flow meter equipped with a pressure transducer attached to the recorder. The sensor was located at 0.34 m (corresponding flow of 0.02 m$^3$/s), and 0.38 m (corresponding flow of 0.10 m$^3$/s) from the bottom of the stream.
channel at Miraflores and Cerro Gordo, respectively. The equipment was programmed to sample composite samples in 9L Nalgene (Nalgene Corp. Rochester, NY) storage bottles. Each storm event sampled corresponded to up to 15 sub-samples of 600 mL increments. The sampler was programmed to sample at varying times which corresponded to specific stage heights based on the expected intensity and duration of the storm-runoff event. A runoff of 1 mm corresponded to 2,240 m³ at Miraflores and 7,147 m³ at Cerro Gordo. The mean sampling depth intervals within specific storm events ranged from 0.33 to 3.70 mm at Miraflores and from 0.24 to 14.80 mm at Cerro Gordo. The sampling times varied from 0.33 to 1.8 hours at Miraflores and from 0.5 to 4.5 hours at Cerro Gordo. Runoff events ranging from 1.22 to 49.2 mm were sampled in Miraflores and from 0.86 to 193 mm in Cerro Gordo. Twenty-three storm events were sampled for each of the subbasins.

After every storm event, the composite bottle was brought to the laboratory for preparation and analysis within a 24-hr period. Samples were processed as described in (Sotomayor et al. 2005; USEPA, 1999).  

Rating Curves: Rating curves for the two sub-basins were required to use the stage data taken by the flow meter and convert that reading to flow. The rating curve was developed from information of the river-reach using the River Analysis System (HEC-RAS, 2002). Cross sections before and after the sampling station were taken with surveying equipment. All topographic data were linked to a grid coordinate system for Puerto Rico (NAD 83, rev 1997). The stage elevation recorded by the flow meter at the site was related to flow based on the site-specific rating curve.  

Hydrologic Analysis: Precipitation data (15-min intervals) was collected in Miraflores subbasin from 1 October 2003 to July 2004. Missing precipitation data for the period August to
September 2004 was estimated using recorded precipitation from nearby USGS stations: 50145395 Río Casey, 50143930 Río Grande de Añasco at Barrio Guácio and 50144000 Río Grande de Añasco near San Sebastián. Precipitation at Cerro Gordo was determined as the weighted average of the other three surrounding stations. Runoff hydrographs of mean daily volume were generated from precipitation data and the SCS-Curve Number method implemented in the Hydrologic Modeling System computer program (HEC-HMS, 2001). Curve Number for soil and land use coverage of each of the sub-watersheds and the time of concentration were calculated from Digital Elevation Models (DEM) files and Digital Ortho Quad Quadrangle (DOQQ) photos that provided the background to delineate homogeneous land use polygons. Daily runoff synthetic hydrographs generated for 2003 were plotted along with instantaneous runoff measured during grab sampling events and storm event dates to match the recorded event with the estimated flow. Most times good match was observed although some other times there was no agreement, this is explained because most times the grab sample was taken mostly during base-glow and elevated base-flow conditions usually prior to storms or at the descending limb of storm events due to safety concerns. Mean daily volumes from the synthetic hydrographs (m$^3$/d) were normalized to volumetric depth units (mm/d).

**Base flow determination.** Miraflores and Cerro Gordo subbasins are ungauged, therefore there is no existing record to perform a low-flow frequency analysis. A gauged station (USGS 50144000 on Río Grande de Añasco near San Sebastian municipality) was used to generate the low-flow frequency analysis for estimating the annual seven days minimum average flow (Riggs, 1972). The low-flow for a recurrence of 25 years was established as the base flow $7Q_{25}$. Base flow was estimated by extrapolation using the ratio of drainage areas method (Gupta, 1989). Runoff flow is proportional to the drainage area and is expressed by:
\[ Q_b = \frac{Q_x}{A_x} A_b \]  

(1)

Where \( Q_b \) is the extrapolated base flow for the un-gauged watershed with drainage area \( A_b \) and \( Q_x \) is the baseflow of the Río Grande de Añasco at San Sebastian with a drainage area \( A_x \). The flow data was separated into baseflow and elevated base flow using the Green and Haggard (2001) criteria: “Samples collected on days when baseflow was greater than or equal to 70 percent of total flow were considered to be baseflow samples”. Surface-runoff (storm event) samples were defined as samples collected on days that base flow was less than 70 percent of total flow (surface runoff was greater than 30 percent of total flow).

Samples were classified as base flow (<0.68 mm/day for Miraflores and Cerro Gordo), elevated base flow (0.69 to 1.21 mm/day for Miraflores and 0.69 to 0.85 mm/day for Cerro Gordo) and storm events (>1.22 mm/event for Miraflores and >0.86 mm/event for Cerro Gordo).

**Estimation of mean daily, and annual loads and yields.** The concentration from the single composite sample represented the event mean concentration (EMC), which is the arithmetic mean of sample concentrations collected on the varying discharge intervals. The load for each constituent for the storm event was determined from the product of the EMC and the integration of the area under the hydrologic discharge curve which corresponded to the runoff volume. The load of each constituent for low-intermediate flows was calculated from the product of the grab sample concentration and mean daily volume. Yields were calculated using the load to subbasin unit area ratio.

Regression analysis using PROC GLM of SAS (Statistical Analysis System, Carey, NC) was used to generate equations relating constituent mass and yields versus runoff depth (mm). In all cases, the data were \( \log_{10} \) transformed to conform with assumptions of normality and variance homogeneity. Regressions were run separately for storm events and low-intermediate flows.
Using data from both subbasins, the following sequence of models was considered: (1) different slopes and intercepts, common slopes and different intercepts and common slopes and different intercepts. The final model was chosen by testing the significance of the regression terms, such that when a non-significant term was found a simpler model was used.

Mean daily loads and yields were calculated using the simulated mean runoff depth and the corresponding equations for storm or low-intermediate flows. On days when a storm event occurred, the constituent mass contribution from the storm event was used. Annual nutrient loads and yields for the water year 2003 (1 October 2003 to 30 September 2004) were calculated based on daily time-series integration of the mean daily loads and yields.

RESULTS AND DISCUSSION

During low-intermediate flow periods, hydrologic flows and SS concentrations were higher in Cerro Gordo but nutrient concentrations were similar between the subbasins (Table 2). During storm events, mean hydrologic flows and SS concentrations were significantly higher (P<0.05) in Cerro Gordo than in Miraflores and there was a tendency for concentrations of TP and TKN to be higher in Cerro Gordo. Mean DP concentrations were higher in Miraflores than in Cerro Gordo.

Empirical annual mean storm sediment yields were 72.4 and 180 kg/ha for Miraflores and Cerro Gordo, respectively. Annual mean storm nutrient yields were 0.013 and 0.023 kg TP/ha, 0.004 and 0.002 kg DP/ha, and 0.067 to 0.114 kg TKN/ha for Miraflores and Cerro Gordo, respectively. Yields of DP were significantly higher for Miraflores. Although constituent (except DP) mean yields were more than double in Cerro Gordo than in Miraflores, these were not statistically different (P>0.05). The greater amount of the total P exported from Miraflores in dissolved form (38% vs. 18%) demonstrates that particulate P associated with sediments is
more important in Cerro Gordo. The DP/TP ratio during storm events (interquartile range of 4 to 43%) was substantially lower than during low-intermediate flows which approached 90%.

During storm events, Cerro Gordo subbasin had higher flows (Table 2), but runoff depths were similar in Miraflores (6.28 mm) and in Cerro Gordo (8.89 mm). For all constituents except DP, the regression coefficient using load (in the abscissa) was higher than when using yield, therefore predictive equations using loads were used for SS, TP, and TKN. Improved predictions between runoff depths and constituent loads and yields were obtained for SS loads, followed by TP loads and DP yields and were lower for TKN loads with regression coefficients ($r^2$) ranging from 0.52 to 0.89. For descriptive comparison purposes and for clarity, constituent yields for all parameters are shown in Figure 1, and regression parameters corresponding to the fit of the equations are shown in Table 3. In all instances, the slopes (change in constituent concentration with increase in unit runoff depth) but not the intercepts of the regressions between constituent (SS, TP, DP, or TKN) and runoff depths were similar between subbasins. It appears that the factors governing sediment and nutrient loads varied in a similar manner with increase in runoff depth in the two subbasins. The greater magnitude in mean constituent loads for given runoff depths suggests that there are greater nutrient and sediment inputs in Cerro Gordo, as a result of more intensive agricultural management practices which include tillage operations for crop establishment and weed control and nutrient inputs. The aerial extent of land under agriculture was 145 ha (20.2% of the total area) in Cerro Gordo and was 8.6 ha (3.9%) of the land area in Miraflores.

The high strength of the prediction between SS loads and runoff depths indicates that a major portion of sediment transport is associated with runoff from soils (storm events) with high flows having high sediment concentrations and vice versa. Although the correlation between
flow and SS concentration was significant for both subbasins combined \( (r=0.61; \ P<0.01) \), the
correlation in Miraflores was stronger than in Cerro Gordo \( (r=0.88 \ vs. \ 0.49) \). The soils in the
watershed are clay-dominated and there appears to be well-mixed conditions at the sampling
point. In contrast to SS, correlations among storm-event flows and TP and TKN concentrations
were not significant and correlations with DP were negatively weakly significant \( (r= -0.29; \ P=0.05) \). The lack of correlation between flow and nutrient concentrations may be attributed to
the various mechanisms influencing nutrient transport in both dissolved and particulate form, as
there were storm events of low and high magnitude both having high nutrient concentrations.
Concentrations of TKN was only positively weakly associated with suspended sediments
\( (r=0.42; \ P<0.05) \), whereas DP concentrations were negatively correlated \( (r=-0.34; \ P<0.05) \) with
sediments. It must be kept in mind that the associations among constituents are due to the event
mean concentrations and not to within event variations. A more detailed account of factors
influencing nutrient transport may be seen with flow-interval sampling \( (\text{Harmel et al., 2003}) \).

Nutrient loads and yields are shown in Table 4. Only about 3% of the nutrient loads to
subbasin outlets was contributed during low-intermediate flows. Runoff depths from low-
intermediate flows corresponded to 3.6% the total annual runoff depths quantified from these
subbasins. In addition, nutrient concentrations were significantly greater during storm events.
Yields of TKN were higher in Cerro Gordo than in Miraflores subbasin. The TKN yields
quantified in this study are substantially higher than those reported for undisturbed tropical
watersheds of the Americas which averaged 3.5 kg N/ha (total N minus nitrate-N) \( (\text{Lewis et al. 1999}) \), and are higher for three undisturbed watersheds of Puerto Rico (4.95 kg N/ha) \( (\text{McDowell and Asbury, 1994}) \). In contrast our values are within N export values of (33 kg total N/ha)
reported by Ortiz-Zayas (2006) in the Rio Grande de Añasco watershed Puerto Rico, which were
estimated from historical nutrient and streamflow data. A portion of the amount of N exported from Miraflores and Cerro Gordo may be unaccountable, because NO$_3^-$ was not quantified in the samples. Nitrate concentrations have been observed to be up to 90% of the total N in these surface waters during low-intermediate flows, but may account for a lower portion of total N losses during storm events. The nitrate-N contribution to the total N export yield may approximate 30% (Clark et al., 2005).

During both low-intermediate flows and storm event DP concentrations were higher than in Cerro Gordo, which contributed to higher DP yields in Miraflores. It is not clear as to why this pattern occurred except that a greater portion of orthophosphate may be associated with iron-oxide clayey sediments transported in Cerro Gordo, and hence measured as total P. Subsurface interflow due to faulty septic tanks of unsewered households may possibly be contributing orthophosphate to these streamwaters. In addition, direct nutrient inputs of gray-water discharge to ephemeral channels can contribute dissolved forms of nutrients during runoff events. In Miraflores, the land under suburban use was 14% of the total 30-m buffer zone surrounding drainage channels, while Cerro Gordo had less than 2%. The population density in Miraflores of approximately 1,000 indiv./km$^2$ and 430 indiv./km$^2$ of Cerro Gordo are much greater than the threshold value of 5 indiv./km$^2$ for undisturbed watersheds (Lewis et al., 1999).

Yields of TP and SS were higher in Cerro Gordo than in Miraflores. Yields of TP were higher than those observed in temperate areas (Johnes, 1996; Clark et al., 2004), and higher than yields reported in undisturbed tropical watersheds (McDowell and Asbury, 1994). As land-use changes from forest to mixed agriculture and pastures to suburban use the total N and total P export shifts from atomic N:P ratios below 7:1 (Downing et al. 1999). Our N to total P export
values were 4:1, and suggests that human and agricultural activities have influenced N and P cycling in these areas.

**Literature Cited**


Table 1. Land use description of two subbasins within the Rio Grande de Añasco watershed in western Puerto Rico.

<table>
<thead>
<tr>
<th>Uso</th>
<th>Subbasin</th>
<th>Miraflorres</th>
<th>Cerro Gordo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suburban</td>
<td>25.8</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>Agriculture</td>
<td>8.6</td>
<td>144.6</td>
<td></td>
</tr>
<tr>
<td>Herbaceous rangeland</td>
<td>51.7</td>
<td>96.3</td>
<td></td>
</tr>
<tr>
<td>Secondary forest</td>
<td>137.8</td>
<td>393.5</td>
<td></td>
</tr>
<tr>
<td>Managed pasture</td>
<td>0.0</td>
<td>72.3</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>224.0</td>
<td>714.7</td>
<td></td>
</tr>
<tr>
<td>Housing structures</td>
<td>560</td>
<td>776</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Mean nutrient concentrations and flows in two subbasins within the Rio Grande de
Añasco watershed in western Puerto Rico. Mean values with different letters are significantly
different. ANOVA was run using log_{10} transformed data.

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Low-intermediate flows (n=36)</th>
<th>Storm events (n=23)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SS mg/L</td>
<td>TP</td>
</tr>
<tr>
<td>Miraflores</td>
<td>4.06b</td>
<td>0.052</td>
</tr>
<tr>
<td>Cerro Gordo</td>
<td>20.5a</td>
<td>0.052</td>
</tr>
<tr>
<td></td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>
Table 3. Regression parameters corresponding to the fit of the equations relating storm event loads of suspended sediments, total P, and TKN and yields of dissolved P with runoff depth.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Subbasin</th>
<th>Intercept (log10)</th>
<th>Slope (log10)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loads (kg SS)</td>
<td>Cerro Gordo</td>
<td>3.864</td>
<td>1.312</td>
<td>0.889</td>
</tr>
<tr>
<td></td>
<td>Miraflores</td>
<td>3.163</td>
<td>1.312</td>
<td>0.889</td>
</tr>
<tr>
<td>Loads (kg TP)</td>
<td>Cerro Gordo</td>
<td>0.303</td>
<td>0.979</td>
<td>0.854</td>
</tr>
<tr>
<td></td>
<td>Miraflores</td>
<td>-0.337</td>
<td>0.979</td>
<td>0.854</td>
</tr>
<tr>
<td>Yields (kg DP/ha)</td>
<td>Cerro Gordo</td>
<td>-3.820</td>
<td>1.013</td>
<td>0.783</td>
</tr>
<tr>
<td></td>
<td>Miraflores</td>
<td>-3.259</td>
<td>1.013</td>
<td>0.783</td>
</tr>
<tr>
<td>Loads (kg TKN)</td>
<td>Cerro Gordo</td>
<td>1.242</td>
<td>0.702</td>
<td>0.523</td>
</tr>
<tr>
<td></td>
<td>Miraflores</td>
<td>0.613</td>
<td>0.702</td>
<td>0.523</td>
</tr>
</tbody>
</table>
Table 4. Nutrient and sediment loads and yields from two subbasins within the Rio Grande de Añasco watershed in western Puerto Rico.

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>DP</th>
<th>TP</th>
<th>TKN</th>
<th>SS</th>
<th>Loads (kg/subbasin)</th>
<th>Yields (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miraflores</td>
<td>244.6</td>
<td>870.5</td>
<td>3,780</td>
<td>6,887,098</td>
<td>1.09</td>
<td>3.89</td>
</tr>
<tr>
<td>Cerro Gordo</td>
<td>238.5</td>
<td>3,545.8</td>
<td>15,603</td>
<td>31,388,936</td>
<td>0.33</td>
<td>4.96</td>
</tr>
</tbody>
</table>
Figure 1. Relationships between storm runoff depths and total P, dissolved P, suspended sediments, and total kjeldahl N in two subbasins of the Rio Grande de Añasco watershed.