# Report for 2005NY72B: Demonstration assessment of innovative water quality protection options for Cayuga Lake: Fall Creek and Cornell campus

Publications

- Conference Proceedings:
    - Walter, M.T., Fall 2005, Raindrop Driven Transport: Theories and Experiments (INVITED PRESENTATION), Cornell University Department of Civil and Environmental Engineering Water Resources Seminar Series, Ithaca, NY.
- Articles in Refereed Scientific Journals:
    - Shaw, S.B., M.T. Walter, T.S. Steenhuis, 2006, A physical model of particulate wash-off from rough impervious surfaces, Journal of Hydrology, in press.
    - Gao, B., M.T. Walter, T.S. Steenhuis, J.-Y. Parlange, B.K. Richards, W.L. Hogarth, C.W. Rose, G. Sander, 2005, Investigating Raindrop Effects on the Transport of Sediment and Non-sorbed Chemicals from Soil to Surface Runoff, Journal of Hydrology, 308: 313-320.
    - Shaw, S.B., M.T. Walter, 2006, Incorporating Surface Trapping into a Sediment Wash-off Model, ASCE Journal of Hydrologic Engineering, In Preparation.
- Unclassified:
    - Shaw, S.B. and M.T. Walter, 2006, Trapping Efficiency of a Small Reservoir, ASCE Journal of Hydrologic Engineering, In Preparation.
    - Shaw, S.B., M.T. Walter, J.-Y. Parlange, I. Lisle, 2006, Testing a Stochastic Wash-off Model with a Simple Experiment, Journal of Hydrology, In Preparation.
    - Shaw, S.B. M.E. Lebowitz, M.T. Walter, December 5-9, 2005, Physical Modeling of Particulate Wash-off from Rough, Impervious Surfaces (B43C-0296), AGU Fall Meeting, San Francisco, CA.

Report Follows

# DEMONSTRATION ASSESSMENT OF INNOVATIVE WATER QUALITY PROTECTION OPTIONS FOR CAYUGA LAKE: FALL CREEK AND CORNELL CAMPUS

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## STUDENT PARTICIPANTS

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## EXECUTIVE SUMMARY

Despite its small volume in relation to inflow (~0.0003 $m^3$ volume/$m^3$ annual inflow), paired sediment samples taken upstream and at the outlet of Beebe Lake indicate an average sediment trapping efficiency of 30%. And, with nearly 6200 metric tons (mt) of sediment captured in the lake each year, the amount retained is an order of magnitude greater than the estimated sediment load from the Cornell campus, 73 mt. These findings suggest that with more routine dredging and enhancement of flow patterns to eliminate hydraulic dead space, trapping in Beebe Lake could be further increased to offset sediment loads from Cornell, thus utilizing Beebe Lake as a centralized stormwater management structure. However, we caution that before such a plan is adopted, the nature of the two sediment sources, Cornell campus vs. watershed above Beebe Lake, needs to be considered. For example, it is possible that sediment generated from Cornell's abundant parking lots may be more highly concentrated with heavy metals than the largely agricultural sources from further up in the watershed.

## FINAL REPORT

## INTRODUCTION

Beebe Lake is an on-line impoundment of Fall Creek situated near the discharge point of the 326 $km^2$ Fall Creek watershed into Cayuga Lake. With the current lake dimensions established in 1896 after construction of the Triphammer Dam, the lake surface covers 5.4 hectares and has a depth of approximately 1 m based on soundings taken in November 2005. The most notable characteristic of Beebe Lake is its small volume in relation to its upstream contributing area. For instance, the ratio of total volume ($m^3$) to total annual 2005 inflow ($m^3$) is only on the order of 0.0003. Despite, this seemingly minor capacity for trapping sediment, the lake has required periodic dredging with two major dredging events in its lifetime, one in 1929/1930 and another in the late 1980's (Smith 2003). While the need for dredging has generally been considered a maintenance nuisance, in light of recent regulatory requirements in controlling non-point source pollutant loads (US EPA 1993), we can consider sediment captured in Beebe Lake to be sediment that would otherwise have ended up in Cayuga Lake. Therefore, the focus of this report is to quantify Beebe Lake's capacity to retain particulate matter and its associated pollutant load.

While impoundments such as reservoirs and storm water detention basins clearly capture sediments (water resource managers will readily attest), there is surprisingly little standardized information on predicting sediment capture rates. Partially, this dearth of information is due to the wide range of hydrologic inputs, sediment size distributions, and basin hydraulic characteristics. In particular, there is virtually no information for the capture capacity of an impoundment that has a such a small volume to inflow ratio; empirical curves relating the volume/inflow ratio to trapping efficiency typically estimate an efficiency of zero for values less than 0.001 (Verstraeten and Poesen 2000).

Objectives of this work were to:

1. Quantify the sediment trapping efficiency of Beebe Lake using paired samples taken above the lake and at the Triphammer Dam.
2. Estimate the total amount of sediment generated from the Cornell campus and compare to the annual load captured in Beebe Lake.
3. Compare the feasibility of retrofitting campus with localized pollutant management structures or enhancing the trapping efficiency of Beebe Lake to manage sediment originating from the Cornell campus.

Furthermore, in this report we discuss additional research needed to better understand sediment trapping mechanisms within Beebe Lake.

## METHODS and ANALYSIS

*Sediment Collection*

Approximately 75 pairs of 1-liter water samples were collected upstream and at the discharge point of Beebe Lake using a submersible, depth integrated sampler. Sampling frequency varied with more frequent sampling conducted during storm events (Figure 1 – note, a sampling day may include multiple samples). The upstream sample was taken from the Forest Home Drive Bridge (Figure 2), approximately 50 m upstream of a USGS stream gauge (NY 04234000). Conveniently, this sampling location is just downstream of a small waterfall in an area of turbulent flow, thus the sample is considered representative of total suspended solids (TSS) across the entire water column as well as bedload material small enough to fit in collector. The downstream sample was taken at the intake to the hydroelectric facility on the northwest corner of Beebe Lake.

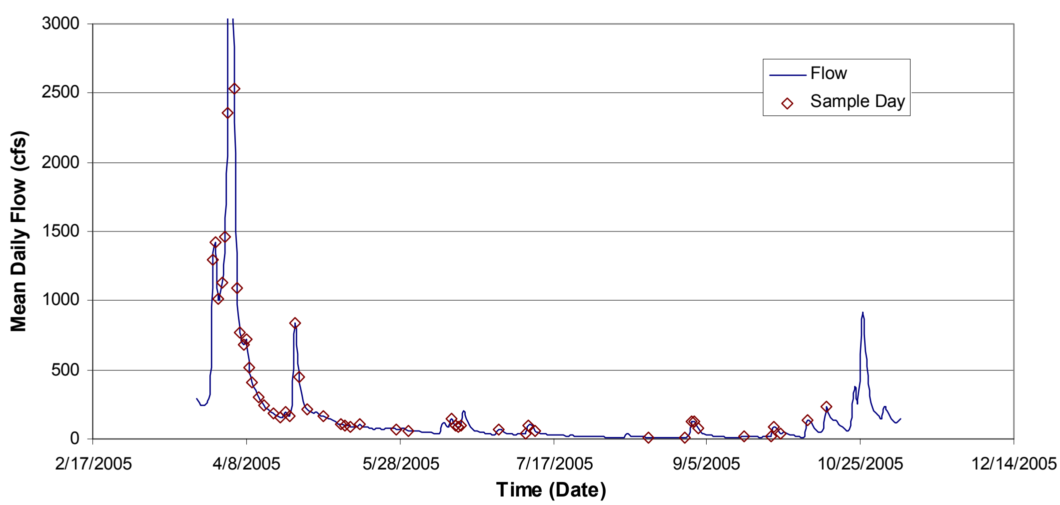


**Figure 1.** Sampling days superimposed on Fall Creek streamflow at Beebe Lake. Note, multiple samples may have been taken on a sample day.

TSS was determined by filtering the stream sample through a weighed Whatman 934-AH glass fiber filter and the residue retained on the filter dried to a constant weight at ~105º C (APHA Part 209C).

These recent data were supplemented with TSS data for Fall Creek collected from the Forest Home Drive Bridge by Dr. Dave Bouldin during the 1970's.


**Figure 2.** Sample site locations overlayed on Beebe Lake aerial photograph, circa 1996. Note, more recently, the more southerly island shown in the photo has been removed.

*TSS Concentration Analysis*

Two primary analyses were conducted on the TSS data: 1.) a comparison of concentrations above and below the Beebe Lake and 2.) the development of TSS rating curves relating TSS and stream flow. In both cases, we found that more predictive relationships could be developed if TSS samples were grouped by the flow conditions at the time of sampling.

Thus, in the case of TSS concentrations above and below Beebe Lake, data were grouped by storm and interstorm periods (Figures 3a and 3b, respectively). Naturally, storm events generate the largest flows, so storm TSS data inherently include the largest flow events and similar results were found if grouped by flow alone (e.g. >100 cfs). Fitting a linear least -squares regression line to the relationships, we find that TSS at the dam is typically 67% of that measured upstream during storm events and 80% of that measured upstream during interstorm periods. An actual retention efficiency was estimated on a mass basis as discussed later. Also, indicated on Figure 3, is a 1:1 line. During storm events, TSS at the dam is always lower than as measured upstream while during interstorm periods, the dominant TSS concentration is less consistent.

For development of the rating curves, TSS samples were grouped among rising hydrograph, falling hydrograph, and interstorm period. For each grouping, linear least-squares regression relates TSS to hourly flow (Figure 4a and 4b). Notably, as shown in Figure 4b, at low flows, flow alone is not a strong predictor of TSS. Complicating factors are likely to include a lag in response in Beebe Lake in comparison to rapid changes in streamflow as well as mixing processes within Beebe Lake that may stir up sediments. However, since low flows contribute a minor amount of the total overall load to Beebe Lake, we did not investigate these processes in this study.

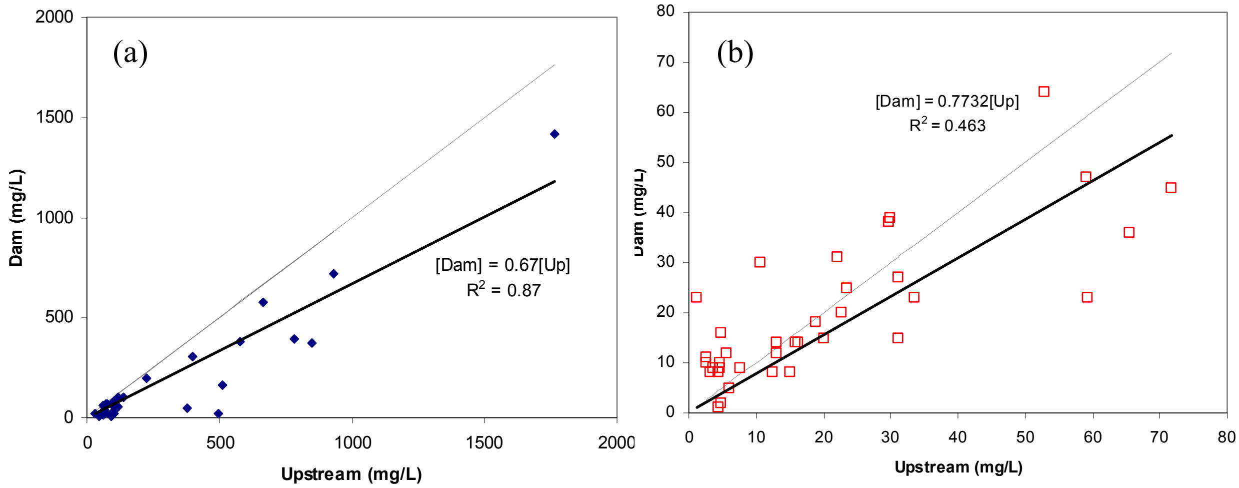


**Figure 3.** Correlation between TSS concentration upstream and at dam for paired samples taken at same time. Figure 3a. is the relationship during storm periods and Figure 3b is the relationship during interstorm periods. The gray line indicates a 1:1 ratio.

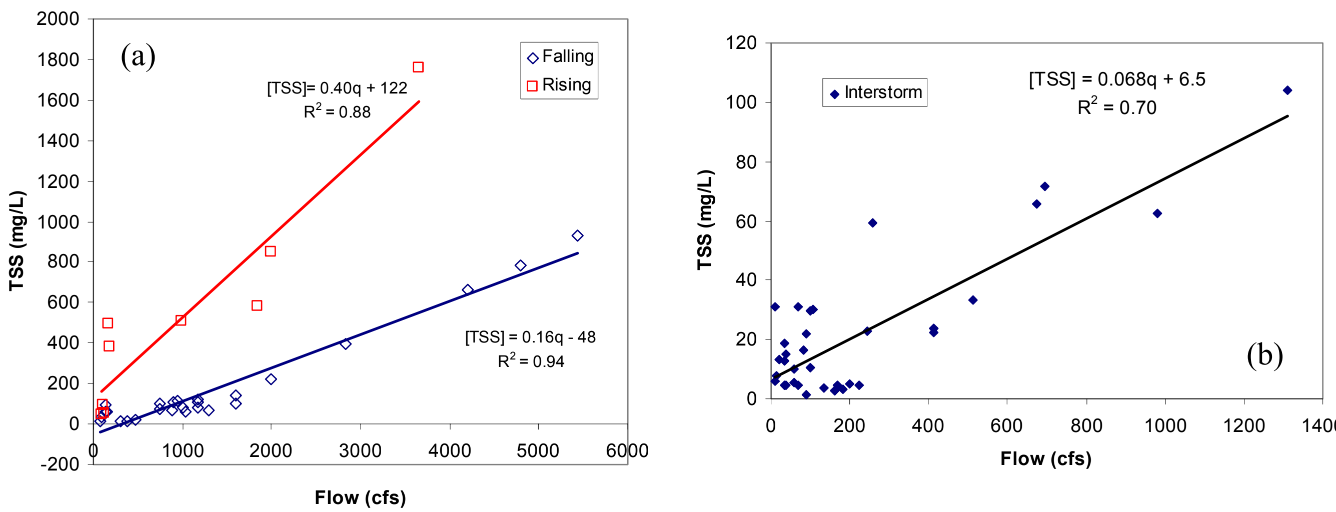


**Figure 4.** Rating curves relating TSS to Fall Creek flow.

Actual loads to Beebe Lake are dependent on the frequency distribution of flows. To estimate loading, we carried out an hourly time step simulation using 2005 hourly Fall Creek along with the rating curve equations presented in Figure 4. For each hourly time step, we classified the associated flow as being either within a rising, falling, or interstorm period. The hydrograph was considered rising if the flow at $T_{i+1}$ was 5% or greater than the flow at $T_i$. The hydrograph was considered falling if the flow at $T_i$ was 5% or greater than the flow at $T_{i+1}$ or if the flow on the rising limb was within five hours of its peak (This five hour lag seemed representative based on an analysis of 5 storm events for which frequent samples were taken). Other cases were considered interstorm periods. The mass captured in Beebe Lake was determined by scaling stream concentrations by the regression coefficients portrayed in Figure 3. Hourly TSS load as predicted fro this simulation is shown overlain with flow in Figure 5.

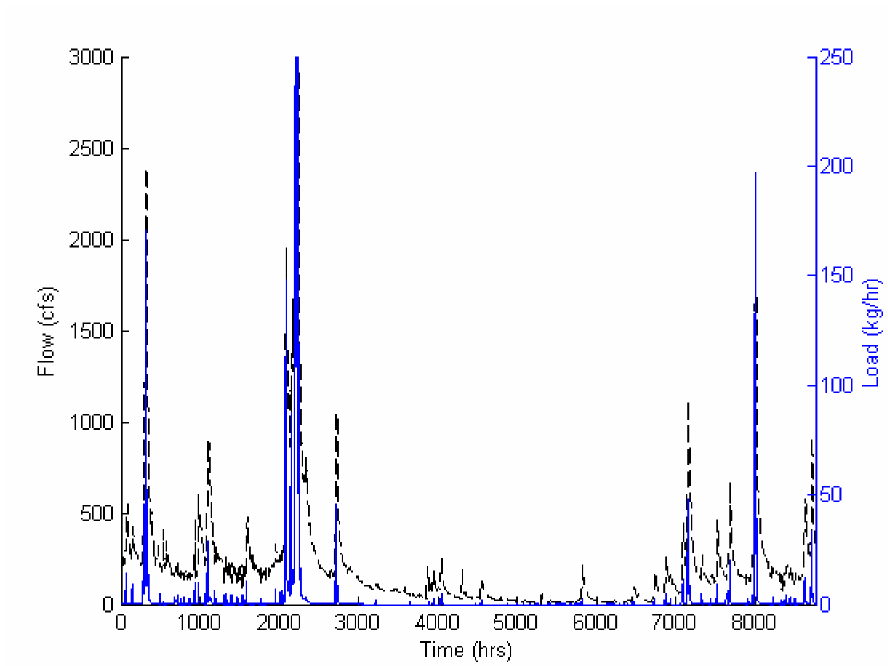


**Figure 5.** Simulated hourly TSS load overlain by hourly flow on Fall Creek. Note, the flow and load on April 2, has been truncated.

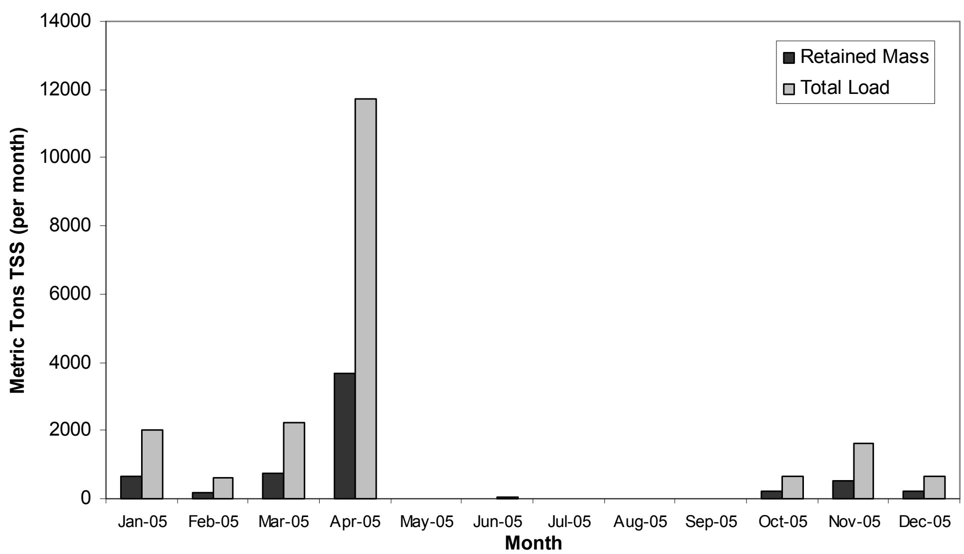


**Figure 6.** Monthly TSS mass loads entering Beebe Lake and retained within Beebe Lake.

Aggregating to a monthly interval, the TSS load entering Beebe Lake and the mass of TSS retained were determined (Figure 6). As apparent in Figure 6, loading was highly variable through the year, with the highest loads primarily correlating on periods of largest streamflows.

The annual TSS load entering Beebe Lake in 2005 is approximately 19600 metric tons (mt) while the total amount retained is approximately 6200 mt. As a back-of-the-envelope check, we assume TSS sediment has a density of 1.5 mt $m^{-3}$. Thus, if spread evenly over the 5.4 ha Beebe Lake, the water depth would decrease annually by about 8 cm, a seemingly reasonable amount.

*NPS Campus Load Estimates*

The Cornell Ithaca campus was modeled as a single, lumped hydrologic unit. Despite the diverse land surfaces and complicated placement of pervious and impervious surfaces, variations in the landscape were considered suitably homogeneous in aggregate to justify forgoing more spatially refined modeling. We assumed the campus area total 560 hectares, the land area of the Ithaca campus excluding agricultural research facilities. Average annual runoff was estimated on a daily basis by applying the SCS Curve Number Equation (with CN = 87) to the 2001 to 2005 daily weather record for Ithaca. A TSS load was estimated by multiplying the runoff volume by an Event Mean Concentration (EMC) for TSS. Stormwater sampling of catch basins and outlet pipes on the Cornell campus from storm events on 9/27/05 and 9/29/05 suggest an average TSS EMC of 77 ppm, consistent with literature values of 72.8 ppm for high density residential (Lee & Bang 2000) and a combination of 110 ppm for parking areas to 33 ppm for landscaped areas (Pitt et al. 1995). The total annual TSS load generated by the campus is approximately 73 metric tons.

There is some possibility of retrofitting campus with localized detention ponds and other structural sediment detention measures to reduce this load. However, given that the campus is nearly fully built-out with little unoccupied space, there are few opportunities for constructing such structures. Figure 7 indicates major storm sewer lines and discharge points. The green, dashed arrows indicate areas where enough room may exist in which a stormwater management measure could be constructed, approximately 30% of the total campus drainage area. Assuming a properly sized urban sedimentation basin can remove 50% of TSS over the long-term (Stahre and Urbonos 1990) over 30% of the 560 ha drainage area, the sediment load could only be reduced by 15% to 62 mt.

*Modeling of TSS Settling in Beebe Lake*

Assuming quiescent settling, input well mixed across the water column, and steady state flow, we use the simple overflow rate approach to estimate the critical settling velocity ($v_c$) for particles:

$$v_c = \frac{q}{A} \tag{1}$$

where $q$ is stream flow entering Beebe Lake and $A$ is the lake surface area (5.4 ha). The critical settling velocity is the minimum settling velocity a particle must have for its entire mass fraction to settle out in the basin. Particle fractions with larger settling velocities will entirely settle out. Particle fractions with smaller settling velocities will settle out in the ratio of the respective settling velocity to the critical velocity.

**Figure 7.** Cornell campus map indicating major storm sewer lines and discharge points. Green, dashed arrows indicate discharge lines where it may be feasible to construct a detention basin or other stormwater management structure.

A $v_c$ is calculated for the complete range of flows observed in Fall Creek (Table 1). For Eqn. 1, we assume *A* is only 2.7 ha to account for hydraulically "dead" space in which the bulk inflow has little interaction. During large flows (>1000 cfs), a higher velocity current can readily be seen north of the island tracking directly to Triphammer Dam, not circuitously passing around the island (Figure 2). In addition, using Stokes Law for settling, a $v_c$ is calculated for a range of sediment sizes (Table 2). Comparing Tables 1 and 2, we find that the particle size removed only shifts moderately downward with decreasing flow. At a flow of 100 cfs, up to 20 micron diameter particles would settle out entirely but at a flow of 1000 cfs up to 100 micron sized particles would settle out entirely. While no analysis of the particle size distribution of TSS in Fall Creek has been conducted to date, qualitative observation of water samples during TSS analysis indicates most material is relatively small in size (less than 100 microns). This simple settling analysis indicates that Beebe Lake should be able to settle some fraction of particles in this 100 micron size range even at large flows – consistent with our observations.

While the overflow rate approach is generally independent of depth, it does assume that the depth is great enough so that lateral shear forces do not re-entrain settled particulate material. Assuming a 100 m width and 1 m depth cross-section for a 28 $m^3/s$ flow (1000 cfs), the average velocity would be 0.28 m/s. For designing vegetated waterways, the critical threshold at which erosion occurs is typically considered to be near 1 m/s (Schwab et al. 1993 Table 7.2), relatively far above our presumed velocity currently. But, if the lake continues to fill in at a rate near 8 cm/yr, it would appear that it would begin to reach a threshold at which shear would play a role within the next five to ten years.

**Table 1.** Critical settling velocity in Beebe Lake for a range of stream flows.

| Flow (cfs) | Critical Velocity (m/s) |
|---|---|
| 10 | 1.05E-05 |
| 100 | 1.05E-04 |
| 250 | 2.62E-04 |
| 500 | 5.25E-04 |
| 1000 | 1.05E-03 |
| 2000 | 2.10E-03 |
| 3000 | 3.15E-03 |
| 4000 | 4.20E-03 |
| 5000 | 5.25E-03 |

**Table 2.** Critical settling velocity calculated via Stokes Law for a range of particle sizes.

| American Soil Classification | Particle Diam. (microns) | Critical Veloc. (m/s) |
|---|---|---|
| Clay | 1 | 5.44E-07 |
| Fine Silt | 4 | 8.71E-06 |
| Med. Silt | 13 | 9.20E-05 |
| Coarse Silt | 35 | 6.67E-04 |
| Fine Sand | 175 | 1.67E-02 |
| Med. Sand | 375 | 7.66E-02 |
| Coarse Sand | 750 | 3.06E-01 |

**CONCLUSIONS**

Partially due to the large sediment load originating from the large upstream contributing area, Beebe Lake annually captures a much greater mass of sediment than generated by the Cornell campus. Enhancing the trapping efficiency of Beebe Lake to offset sediment loads from Beebe Lake seems to be more feasible option than retrofitting the Cornell campus with localized detention basins. Specifically, a 5% decrease in hydraulic dead space in Beebe Lake results in 5% decrease in critical settling velocity resulting in a shift of minimum particle size settled from 45 microns to 42 microns (for 1000 cfs flow). For a representative particle distribution in which 80% of total sediment is assumed to be uniformly distributed below 63 microns (small sand) at higher flows (Slattery and Burt 1997, Walling et al. 2000), this would result in a shift from 43% [ 20% sand fraction plus (63-45)/63*0.8] to 47% [ 20% sand fraction plus (63-42)/63*0.8] of TSS available for settling. Normalizing by the actual measured capture rate of 30%, ~3% more of the particle distribution could be fully settled, upwards of 500 mt. While only a rough estimate, this calculation demonstrates the order of magnitude of the enhancement that could be expected. Alternatively, as discussed previously, localized sedimentation basins removing 50% of TSS over 30% of the 560 ha drainage area could reduce the load by only 11 mt.

Modifications to Beebe Lake would require diverting a greater a fraction flow to the southerly side of the existing island either by modifying the shape of the island or installing diversion vanes possibly similar to rock vanes routinely used in channel restoration projects. Additionally, more frequent dredging of the lake would need to occur, primarily to maintain a depth of at least a meter in order to minimize re-entrainment of sediment by shear.

While the paired sampling provided useful empirical information regarding Beebe Lake's trapping efficiency, additional data is necessary to more accurately model potential changes resulting from modifications to the lake. Most critically, the actual particle size distribution at different flow rate is needed. Using a similar calculation as above but with a known particle size distribution specific to Fall Creek would permit more accurate calculation of the benefits of enhancing Beebe Lake trapping efficiency.

**NEW EXTERNAL PROPOSALS** (these build substantially on this project)

**Title:** Characterizing Landscape-scale Transport Pathways of Pathogens using Innovative DNA-based, Nanotech-tracers
**Agency:** USDA NRI-GGP 26. Water and Watersheds
**Duration:** 9/1/2006-8/31/2009
**Request:** $393,614
**PIs:** Walter, M.T., J.M. Regan (Penn State Univ.), D. Luo

**Title:** Developing and Testing an Innovative Approach for Characterizing Particle Transport in Hydrological Systems
**Agency:** NSF-EAR Hydrology
**Duration:** 1/1/2007 - 8/31/10
**Request:** ~$500,000
**PIs:** Walter, M.T., D. Luo

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