An analysis of the nutrient removal capacity of agriculturally impacted vs. restored riparian wetlands.

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Abstract:

Alteration of the hydrologic properties of riparian zones for agricultural use is a widespread, worldwide practice. In order to understand the consequences of agriculture on streams, solute addition experiments were performed on four streams: a cranberry bog, two restored cranberry bogs, and a natural riparian ecosystem. The results of the experiment quantified transient storage and nutrient uptake in the streams, and also correlated easily identifiable physical properties such as submerged vegetation, emergent marsh, and baffles to actual transient storage present in the streams. The results showed that the natural stream exhibited high amounts of transient storage, the cranberry bog showed very little, and the restored streams exhibited an improvement in transient storage area over the cranberry bog. No nitrate was taken up in any of the streams, but phosphate was taken up in streams that exhibited transient storage. It was concluded from this study that removal of transient storage zones for agricultural practices results in the end of the valuable ecosystem process of nutrient uptake and removal.

Key words: *riparian zones, transient storage, nutrient uptake, agriculture, hydrology, solute dynamics*

Introduction:

Land-use is by far the dominant anthropogenic impact on the earth's ecosystems, and of all land use practices, the most widespread is agriculture (Foley 2004). Deciduous forests, rainforests, and wetlands are all targeted for agricultural use. The case of agricultural use of wetlands creates a unique problem. The widespread practice of agriculture results in high loadings of nutrients to the world's waterways, either through direct fertilizer runoff or from human consumption of agricultural products. When wetlands are drained and channelized for agricultural use, their natural ability to sequester and remove nutrients is inhibited. A vicious cycle develops, in which high population densities result in greater nutrient loadings to waterways, and the agricultural needs of the population further remove the waterway's natural ability to cleanse nutrients from the system by removing riparian wetlands.

This problem is not unique to any location; rather, agricultural use of wetlands is a worldwide practice. From the cranberry bogs of Massachusetts to subsistence farming in Uganda, wetlands are commonly drained and channelized, contributing to high nutrient loadings in lakes and estuaries. The end result is greater eutrophication, which causes unsightly algal blooms and low oxygen conditions harmful to aquatic life.

In past experiments, it has been found that although harvest in cranberry bogs results in some export of nitrogen from the system, there is very little denitrification occurring in the bogs (Howes & Teal 1995). In fact, some cranberry bogs have been shown to be net exporters of nutrients into the streams (Copeland 2002).

In order to remedy the problem, we can restore agriculturally impacted wetlands to natural riparian conditions. Increasing aquatic vegetation and leaf pack and slowing water velocity creates more advection-dispersion and allows for more areas of transient storage, which can reduce the nutrient loading exiting the wetland area (Webster & Ehrman 1996).

Before restoring a riparian zone, it should be compared to similar natural ecosystems in order to better understand the goals of restoration. One way to compare streams is by their area of transient storage and the rates at which they take up nutrients. This comparison can be carried out with a solute addition experiment. These experiments provide vital information on "the integrated physical, chemical, and biological properties of a stream ecosystem" (Stream Solute Workshop 1989).

Solute addition experiments measure transient storage in streams with the use of a conservative tracer. These tracers can range from bromide or lithium to Rhodamine dye, but perhaps the most common is chloride (Stream Solute Workshop 1989). When the solute is added to the stream, concentrations of chloride can be measured at regular time intervals downstream. The result is a plateau shaped curve of chloride concentrations during the experiment, the rise and fall of which provides information on the size of the transient storage area in the stream. An abrupt rise and fall indicates little transient storage, but a gentle rise and fall to and from plateau concentrations shows that there is lots of transient storage, because the chloride does not reach the sampling point all at once.

Nonconservative solutes such as nitrate, phosphate, or ammonia are added during the addition to provide data on the uptake rates of those solutes in the stream. Samples are taken at distances downstream of the addition point before the experiment begins and during the time when chloride concentrations are known to be at plateau. Uptake rates are then determined from the difference between background concentrations and plateau concentrations of the solute at intervals downstream.

The nutrient uptake follows an exponential decay, so that the concentration at any point downstream is described by

$$C = C_0 e^{-kx}$$

where C is the concentration at station x, Co is the concentration at the beginning of the reach, k is the uptake rate, and x is the distance downstream.

Although this type of experiment provides data on the functioning of the whole ecosystem, the mechanisms of uptake are not made clear. Uptake could occur through plant or bacterial use of the solute, or through abiotic complexation of the solute with particles on the streambed. In order to pinpoint the exact sites where uptake is occurring, stable isotopes could be added to the stream, such as in the study by Peterson et al (2001).

Even though nutrients are taken up in streams, there is also regeneration of those nutrients into available forms. This cycle of uptake and regeneration is referred to as the "spiraling length" (Stream Solute Workshop 1989). The length consists of two parts, an uptake length, or the length the average molecule must travel before it is taken up, and the turnover length. Although uptake of nitrogen through denitrification removes N from the stream ecosystem completely, most forms of uptake will have a corresponding regeneration where nutrients are returned to the system. Even so, uptake is a positive ecosystem function because it locks nutrients into unavailable forms, either sorbed to particles or as a constituent of organic matter, where they can be buried in estuaries or flushed out tidally before they are regenerated.

Methods:

In order to quantify the nutrient removal capability of riparian wetlands, solute addition experiments were performed on four riparian sites. The test sites were Lower Bog on the Coonamesset River, a restored cattail marsh on the upper Quashnet River, a fish-habitat restoration area on the lower Quashnet, and an undisturbed location on the lower Mashpee River.

Flow rates in these rivers were measured using a Marsh-McBirney Flowmate. By combining these flow rates with background nutrient concentrations gleaned from literature (Gocke 2003), I was able to use the principle of conservation of mass to calculate how much solute I would have to add to the rivers (Table 1).

Based on the flow rate of each river, a reach length, or the length of stream over which the experiment would be conducted, was determined. In most cases the reach was 400 m long, but in the case of the cattail marsh this length was limited by a large incoming stream at 210 m. This particular length was chosen based on the relationship given by Peterson et al, in which a stream with a flow between 200 and 300 L/s would have an uptake length (S_w) of about 400 m (Fig 1). Along this reach, sampling stations were flagged at 25, 50, 100, 150, 225, 300, and 400 m.

I then placed Hydrolabs at the 50 and 400 m stations. These Hydrolabs were configured to automatically log conductivity data at regular intervals. By adding NaCl as a solute during the nutrient addition experiment, conductivity would rise and provide data on advection-dispersion and transient storage.

Just before beginning a solute addition experiment, samples were filtered and collected into scintillation vials from the 7 sampling stations. These samples would later be analyzed for nitrate and phosphate to determine ambient nutrient concentrations.

Nutrient solution was prepared in the field by heating water and adding the desired amounts of NaCl, $NaNO_3$, and $NaHPO_4$. Then, approximately 100 L of this solution was poured into a Mariotte bottle. The Mariotte bottle was bled until a vacuum formed inside and the flow became constant. The outlet height was adjusted to obtain a flow of 300 mL/min from the Mariotte bottle. To obtain increased mixing of the solute with the river water, the solution was dripped into the river with a meter long spreader bar, a rigid PVC pipe perforated with several small holes.

After allowing the solution to drip into the river for several hours, and when the downstream Hydrolab read a constant level of conductivity above background, samples were again filtered into scintillation vials at all of the sampling stations. Samples were collected from downstream to upstream in order not to cause contamination by walking in the stream.

After post-addition samples were taken, I used a hand-held conductivity meter to measure conductivity along cross sections at each sampling location and determine the extent of the nutrient solution's mixing with the river. Flow rates were also measured at the downstream and upstream boundaries in order to determine if any lateral input of stream or groundwater was present.

At each sampling station, the cross sectional area of the stream was determined. Then, at intervals across the stream, a quantitative stream condition assessment was performed. This process involved determining what material was on the streambed, such as sand, leaf pack, submerged vegetation, etc. The amount of points that could be considered as possible transient storage or fish cover were tallied and then expressed as a percentage of the total points surveyed.

Upon return from the field, samples to be analyzed for nitrate were frozen and samples to be analyzed for phosphate were acidified with 5 N HCl and refrigerated.

Nitrate samples were analyzed using a Lachat, while phosphate samples were analyzed colorimetrically on a Schimadzu spectrophotometer. Samples were also run on a Dionex Ion Chromatograph to determine chloride concentration.

Hydrologic data obtained from the Hydrolab conductivity tracers was analyzed using the USGS OTIS-P model for stream flow. This model provided quantification of hydraulic residence times, advection-dispersion coefficients, and transient storage.

Results:

Out of the four sites, hydraulic data was collected for all four, nutrient data for all but the lower Quashnet, and streambed assessment was performed on all but the cattail marsh. The Quashnet nutrient data was complicated by two factors. There was a storm preceding the experiment, which the Stream Solute Workshop says can "alter the potential for solute uptake" (1989). Secondly, there may have been contamination problems with either the filters or sample vials used, as replicate samples gave values far outside acceptable variation. Streambed assessment was not performed on the cattail marsh due to time constraints.

With those facts in mind, there were at least three streams to compare in each of the three factors analyzed: hydraulic data, nutrient uptake, and streambed assessment.

Hydraulic Data-

The conductivity data taken by the Hydrolabs was converted to mg L^{-1} of chloride based on a calibration of one of the Hydrolabs. Then, because one Hydrolab was calibrated differently, its values were adjusted by a second calibration factor to bring the plateaus to the same height. The assumption was that dilution was minimal compared to the flow in the stream, and based on upstream and downstream measurements of flow during the experiments, this was in most cases true.

The chloride data was then fit with the OTIS-P model, and in most cases the model fit was quite good (Figures 2-5). The only exceptions are on the Mashpee and the cattail marsh. On the Mashpee, the data is somewhat complicated because the stream is a tidal freshwater stream, and therefore its flows differ significantly during the day. We performed the experiment during the ebb, but the water may have been backed up at the beginning of the experiment or may have begun to back up at the end, which would have shifted the arms of the chloride plateaus in a way that the model could not adjust for. On the cattail marsh, the Mariotte bottle became clogged about an hour after the drip began, lowering the flow rate of the solute injection. However, nutrient samples were still taken during the plateau portion of the curve and also the model was able to be adjusted for the change in injection flow rate.

The output of hydraulic parameters from the OTIS-P model shows that there was a significant amount of transient storage, 0.776 m^2 in the average cross section, in the Mashpee river, which I considered to be a natural ecosystem (Table 2). The cattail marsh and the Quashnet, the two restored streams, showed 0.022 and 0.231 m^2 of storage cross sectional area, respectively. The cranberry bog showed only 0.002 m^2 of transient storage in its average cross section.

While the Mashpee, Quashnet, and Coonamesset all had similar flow rates in the range of 0.25 to 0.35 $m^3\ s^{-1}$, the cattail marsh exhibited a much lower flow of 0.014 $m^3\ s^{-1}$. Because of these differences in flow, it was important to normalize the average cross-sectional area of storage for the size of the stream. By doing this a more accurate comparison of streams of different sizes can be presented. I did this in two ways, by normalizing for flow and normalizing against channel area.

To normalize for flow, the transient storage cross-sectional area was divided by the flowrate of the river (Table 2). This resulted in a spectrum of ratios with the Mashpee again showing the highest amount of storage, the restored streams an intermediate amount, and the Coonamesset cranberry bog showing next to none (Figure 6). It is significant to note that although the cattail marsh had a small cross-sectional area of storage, 0.022m^2, it actually showed the second highest storage-to-flow ratio.

The second method of normalization was to divide the cross-sectional area of storage by the cross-sectional area of the channel, or the area that is not storage. Once again, the Mashpee ranked with the highest ratio of 0.437, which means nearly a third of the stream's size is devoted to storage. The cattail marsh and Quashnet showed similar ratios, 0.081 and 0.141 respectively, which shows that somewhere around a tenth of their area is storage. The Coonamesset cranberry bog showed a ratio of 0.01, which means less than one percent of the stream's cross-sectional area is storage (Figure 7).

A few other hydraulic parameters of note are the residence time and the the storage zone transfer rate. The hydraulic residence time is the length of time that it takes for the downstream chloride curve to reach plateau normalized for the length of the stream. The Coonamesset and Quashnet had similar residence times of 0.13 and 0.14 min m^{-1}. The Mashpee and cattail marsh showed similar residence times also, of 0.46 and 0.43 min/m respectively. The storage zone transfer rate indicates how quickly water is exchanged between the channel area and the storage zone. The cranberry bog had the slowest transfer rate, which means that once water goes into a storage zone there, it stays for a long time. The cattail marsh had the second lowest transfer rate, and the Mashpee and Quashnet had similar high transfer rates, which indicates that the water is easily exchanged between their storage zones and the channel (Table 2).

Nutrient Uptake-

The three streams analyzed for nutrient uptake were the Mashpee, the cattail marsh, and the Coonamesset cranberry bog. Two nutrients were analyzed; nitrate and phosphate. Comprehensive nutrient and chloride data can be found in Table 4. In all three streams, there was no discernable uptake of nitrate (Fig 8-10). The Mashpee and cattail marsh both took up phosphate, but the Coonamesset did not (Fig 11-16).

Uptake rates of phosphate were 0.0038 m^{-1} for the Mashpee and 0.0049 m^{-1} for the cattail marsh. The corresponding uptake lengths for these streams, which can be found by taking the reciprocal of the uptake rate, were 263 m and 204 m respectively (Table 3).

Typically nutrient concentrations are adjusted by the relative concentration of the conservative solute to adjust for dilution. Although in most cases the chloride concentrations showed an even plateau down the length of the reach, in some cases there were significant outliers. The few outliers all showed extremely high chloride concentrations, which would not indicate dilution. For this reason, nutrient concentrations were not adjusted, but it was instead assumed that there was even mixing and no dilution (Table 4).

Streambed Assessment-

The streambed assessment yielded several different stream bottom cover types. Areas of submerged vegetation, emergent marsh vegetation, mud, leaf pack, and behind man-made baffles and overhanging banks were classified as areas of possible transient storage, while areas of sand, gravel, or wood were not. The Mashpee, the most natural of the ecosystems studied, had 83% of its stream bottom identified as possible areas of transient storage. The Quashnet had 49% possible transient storage, and the Coonamesset had 31% (Table 5).

The streambed assessment of possible transient storage showed quite good correlation with actual transient storage data. Possible transient storage had a 0.98 R^2 correlation with the storage/flow ratio and a 0.998 R^2 correlation with the storage/channel ratio (Figs 17, 18). There was also a fairly good correlation of in-stream vegetation to storage (Fig 19).

Discussion-

Even from visual inspection of the chloride plateaus, it is evident that out of the four rivers, the Coonamesset is the only one that shows almost no evidence of transient storage (Figs 2-5). Results from the OTIS-P model serve to back up what seems obvious. It would seem as little coincidence then that the Coonamesset is also the only river that exhibited no nutrient uptake of any kind. Therefore it seems that altering the hydraulics of a riparian zone for agricultural use does indeed have detrimental effects on the stream's ability to take up nutrients.

Although there is not a very evident trend between storage ratios and uptake rates, what does seem clear is that there must be transient storage in order for uptake to take place (Figs 20, 21). The reason for the absence of an obvious trend is because transient storage alone is not the only factor that comes into play in solute dynamics. Different substrates and the types of biota, both bacteria and plants, that are present in these zones of storage are also responsible for differences in uptake rates. In the end, it is a combination of hydrology and biotic/abiotic processes that results in uptake. Storage areas that are empty of anything biological, for example an eddy behind a man-made baffle, will result in no uptake; likewise, biotic and abiotic processes that act on the nutrients can only occur in areas where the water has slowed down, in areas of transient storage.

As far as nutrient uptake is concerned, I observed significant uptake of phosphate in some streams but no streams showed uptake of nitrate. If phosphate is taken up, then by ecosystem stoichiometry, some nitrate also must be taken up. However, the loading of nitrate to these streams was very high, while phosphate levels were very low. Therefore, it would have been very difficult to see the nitrate uptake that corresponded to an equivalent uptake of phosphate. Also, uptake of N to match the uptake of P could have occurred in the form of ammonia, whose uptake length is known to be very short, almost 5 times as small as that of nitrate (Peterson et al 2001). In addition, P uptake could have been abiotic, which would not require any N uptake at all. Finally, these experiments were performed during the late fall when denitrifying bacteria could be slowing down their activity. All these reasons could help to explain why there was no uptake of nitrate in any of the streams.

Another conclusion that can be gained from this experiment is that actual sight-identification of streambed conditions that represent possible transient storage correlate well to actual hydrologic conditions. This kind of data could be very valuable to managers who wish to restore riparian zones for nutrient uptake.

One important thing to notice from the correlations of possible transient storage to actual storage is that around 30% possible transient storage, actual storage is near 0. When performing a streambed assessment, I may have, for instance, come across an isolated patch of submerged vegetation. This would be classified as possible storage, but because of its location, size, and isolation, it did not contribute to any real storage. It seems from Figures 17 and 18 that there is a threshold when enough possible storage areas build up that actual storage begins to take place.

The streambed assessment is also valuable because it helps managers and engineers put a concept like transient storage into actual physical, designable terms. Without extremely sophisticated calculations and models, it would be difficult to know for sure what kind of storage a restored riparian zone or wetland would exhibit. If more data were compiled of this kind, it could serve as a useful tool for managers in charge of restoration who perhaps do not have a rigorous hydrologic background. These tools would give the managers an idea of how much transient storage they would gain by installing deflectors and baffles, planting with submerged vegetation or marsh, or surrounding with terrestrial vegetation in order to supply leaf pack and other detritus.

The stretch of the Coonamesset that I studied, Lower Bog, is currently slated for restoration. It is interesting to note that uptake lengths that I measured in the Mashpee and the cattail marsh were 263 and 204 m, respectively. The length of Lower Bog is close to 400 m long. This means that the restored length would be almost twice the uptake length of phosphorous that occurs in restored and natural streams. Therefore, as far as the restoration of Lower Bog for nutrient uptake is concerned, it would be quite useful to restore this 400 m stretch of the Coonamesset.

The final conclusion is that riparian restoration serves several functions, one of which is nutrient uptake, another of which is fish habitat. My collaborator, Kingsland, found that the Mashpee and Quashnet exhibited benthic and fish communities that were indicators of good water quality, whereas the Coonamesset had communities indicating poor water quality. He also found that the Mashpee and Quashnet had much more available fish habitat, wheres the Coonamesset had very little. The correlation between all depth-independent habitat areas and the amount of transient storage is a very strong one, showing that restoration serves the functions of fish habitat and nutrient uptake simultaneously (Figure 22).

Acknowledgements-

This project could not have been completed without the tireless help of many wonderful people at my side. Linda Deegan provided lucid insights into not only the mechanics but also the value of stream ecology. Rich McHorney worked tirelessly in the field and on errands and saved the project from certain delay on several occasions. Heidi Wilcox’s cheer was much appreciated, as was Suzanne Thomas’s vast experience with solute dynamics. Special thanks goes out, of course, to Sarah Hicks, who had plenty of other responsibilities but really helped out in a pinch. Also, none of the data analysis for this project could have been completed without the efforts of Allison Burce and Ian Washbourne.

Thanks to Kevin Kingsland. There is nobody more good-natured or patient in all this program. Working in the field past sunset almost every day might have been torture had it not been for his unique brand of humor.

I would also like to point out the great thanks I have for my field sites, whose beauty and power were a constant source of inspiration.

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Table 1. Target concentrations for solute injection.

		Mashpee	Coonamesset	Cattail Marsh	Quashnet
Flow	(m^3/s)	0.244	0.252	0.14	0.23
Ambient Nitrate	(uM)	24	14	23	23
Ambient Phospate	(uM)	0.8	0.9	0.7	0.7
Target Nitrate	(uM)	72	42	69	69
Target Phosphate	(uM)	2.4	2.7	2.1	2.1
Rate of Injection	(mL/s)	5	5	5	5

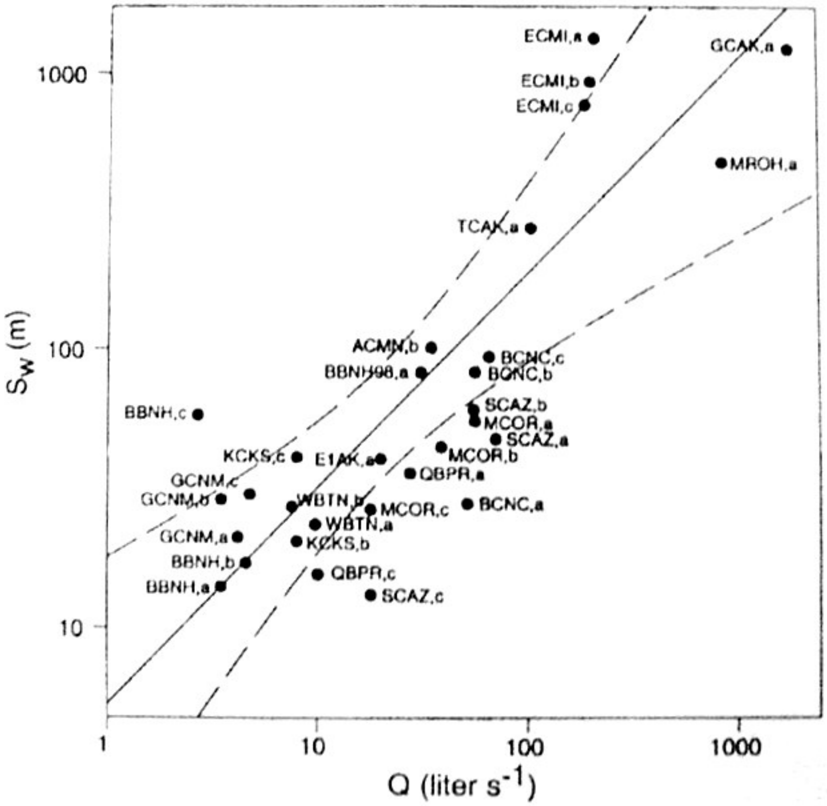

Figure 1. Relationship of flow rate to nitrogen uptake length. (Peterson et al 2001).

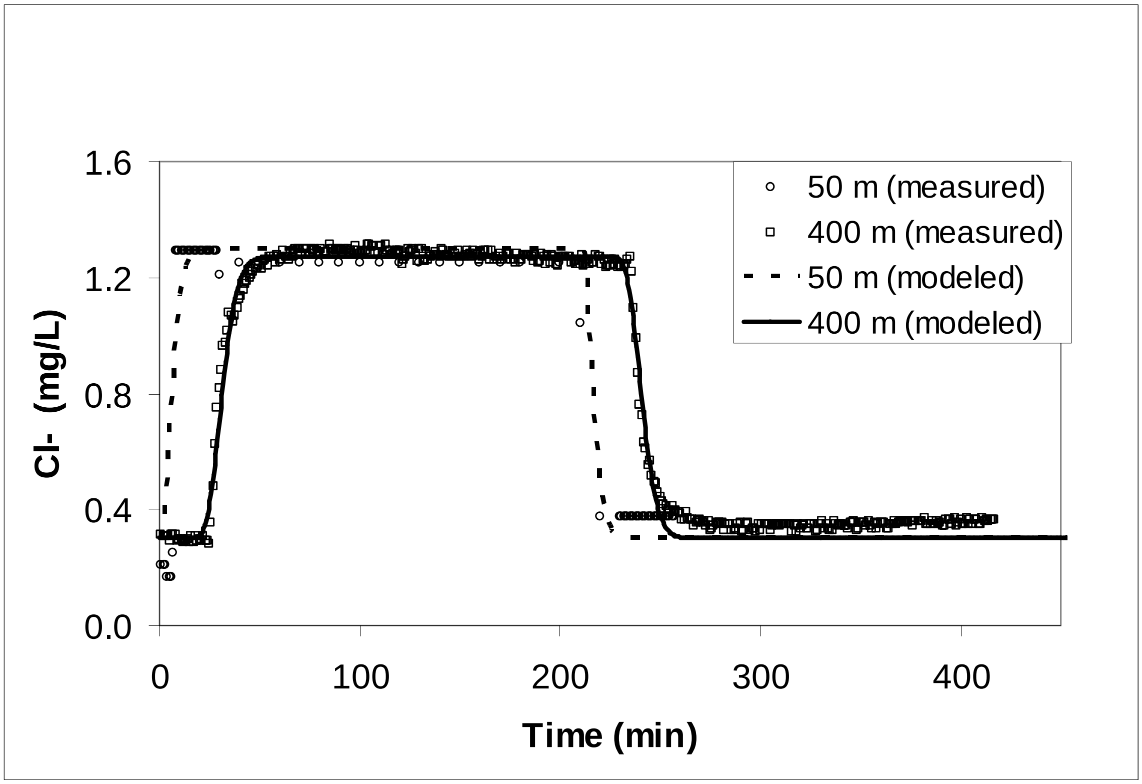

Figure 2. Chloride concentration vs. time for the Coonamesset

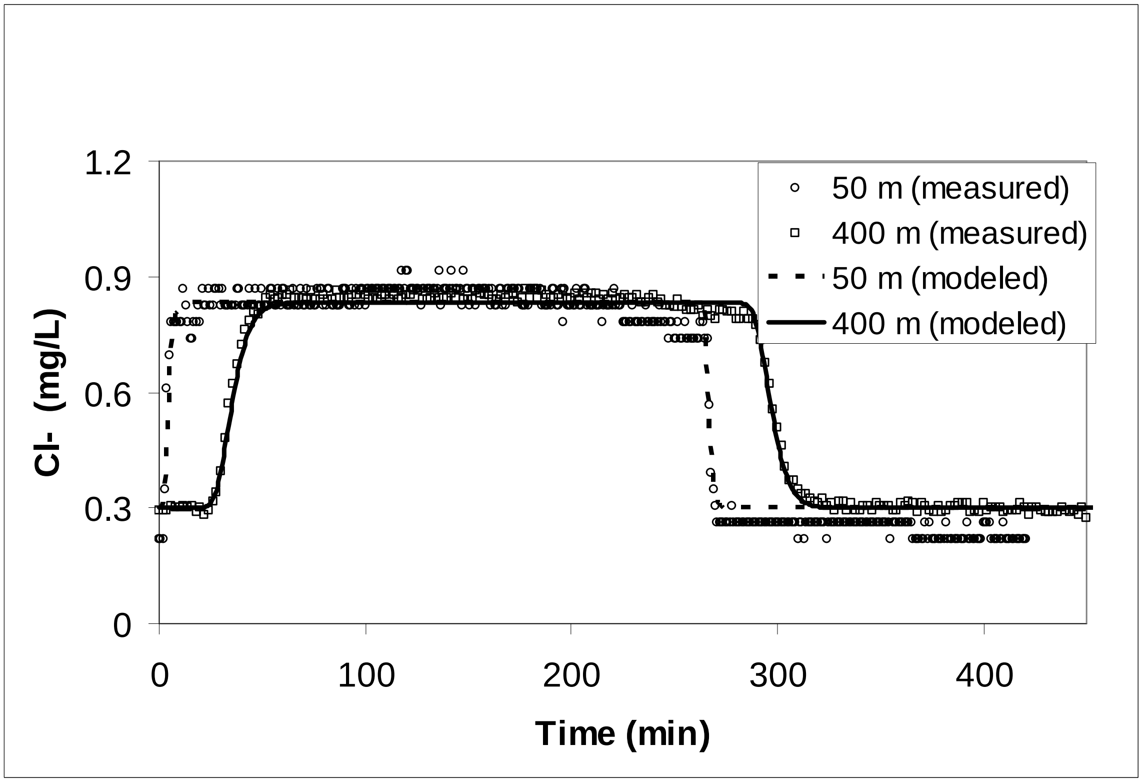

Figure 3. Chloride concentration vs. time for the Quashnet

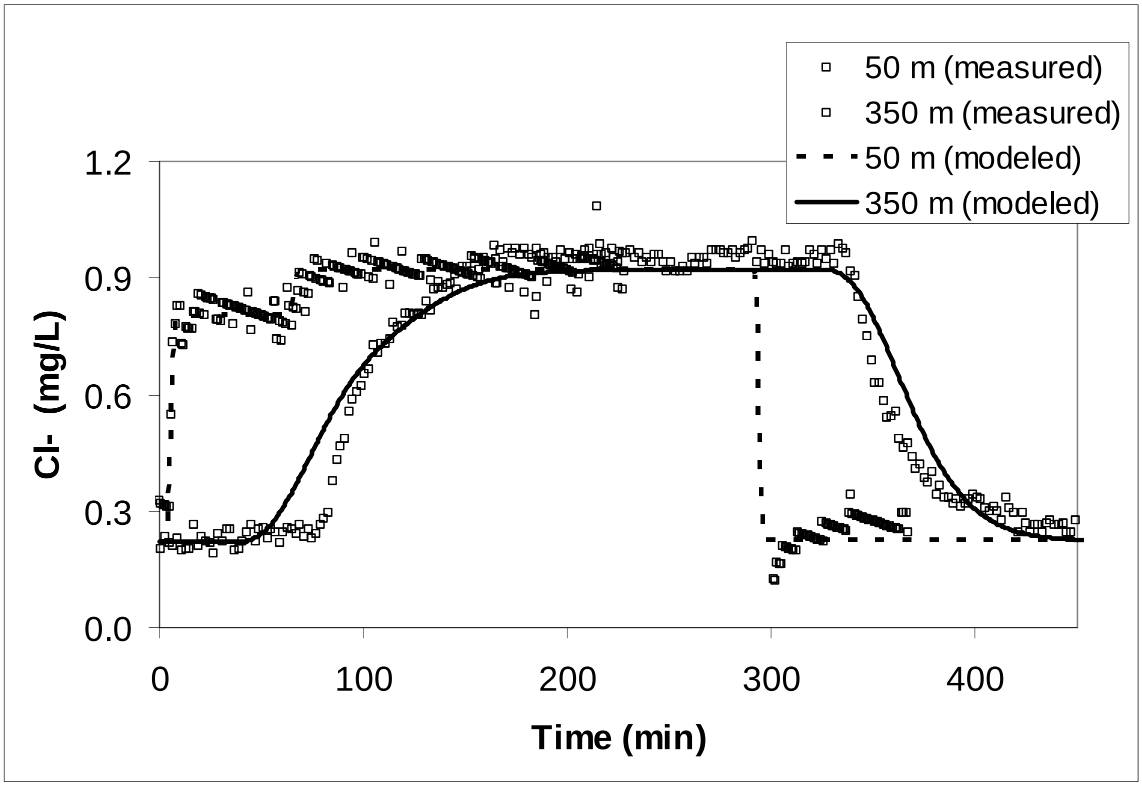

Figure 4. Chloride concentration vs. time for the Mashpee

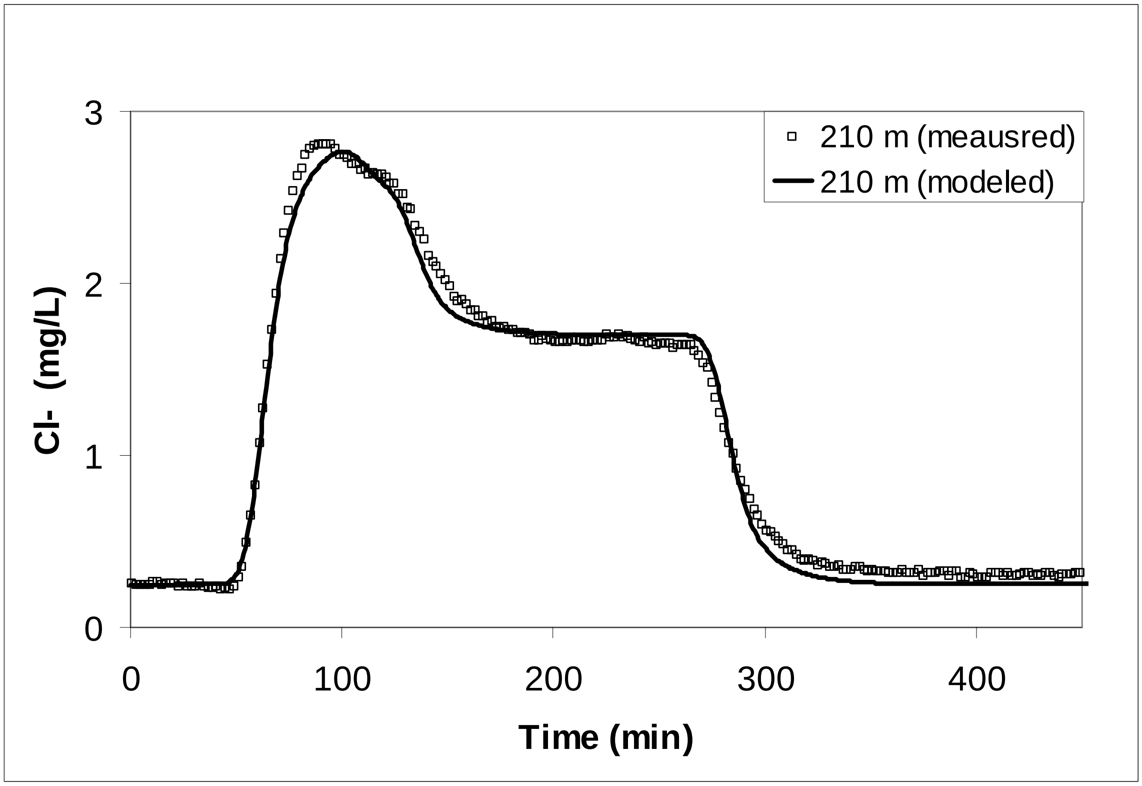

Figure 5. Chloride concentration vs. time for the cattail marsh.

Table 2. Summary of OTIS-P model output.

		Mashpee	Coonamesset	Cattail Marsh	Quashnet
Upstream Flow	*(m^3/s)*	0.237	0.238	0.014	0.347
Downstream Flow	*(m^3/s)*	0.289	0.233	0.02	0.341
Channel Area	*(m^2)*	1.639	1.226	0.237	1.638
Transient Storage	*(m^2)*	0.776	0.002	0.022	0.231
Storage/Channel Ratio		0.437	0.002	0.081	0.141
Storage/Flow Ratio	*($m^2/(m^3/s)$)*	3.27	0.01	1.57	0.67
Dispersion Coefficient		0.1334	1.5382	0.0899	0.9961
Hydraulic Residence Time	*(min/m)*	0.46	0.13	0.43	0.14
Transfer Rate		1.42E-03	6.42E-07	9.86E-05	9.67E-04

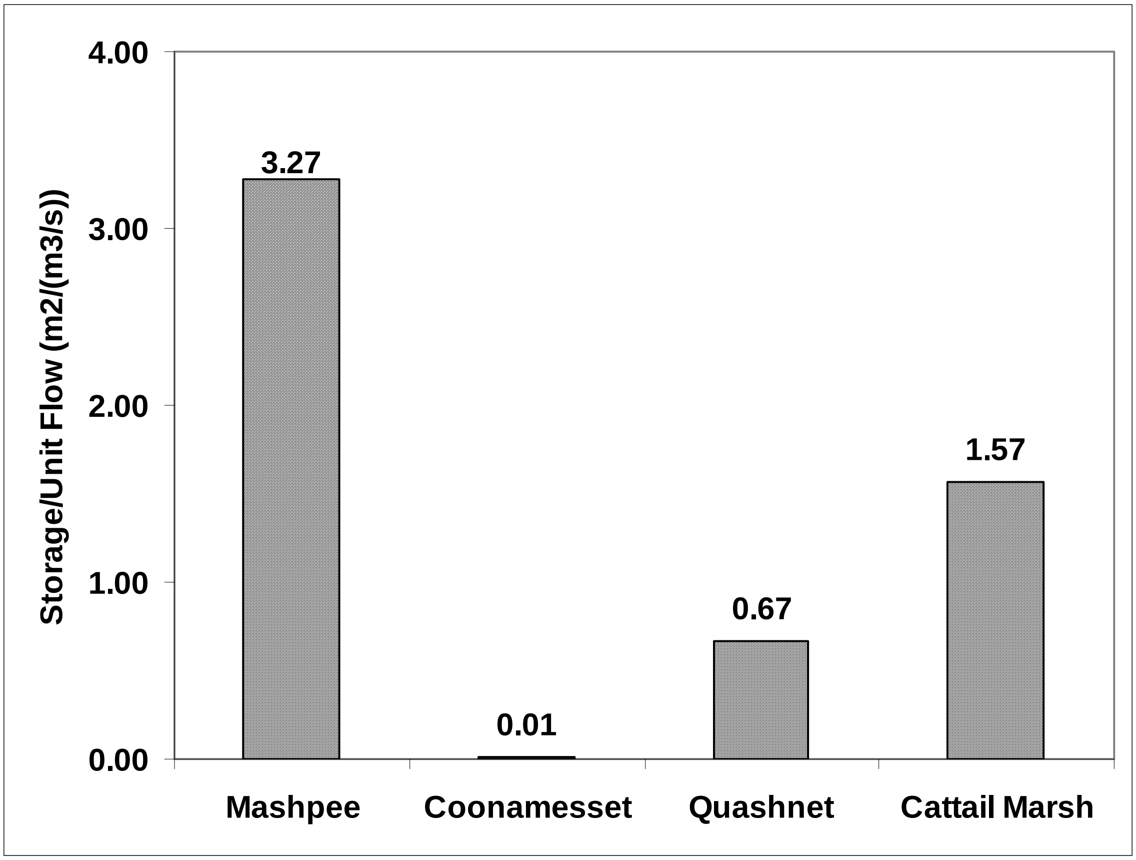

Figure 6. Storage per unit flow ratios

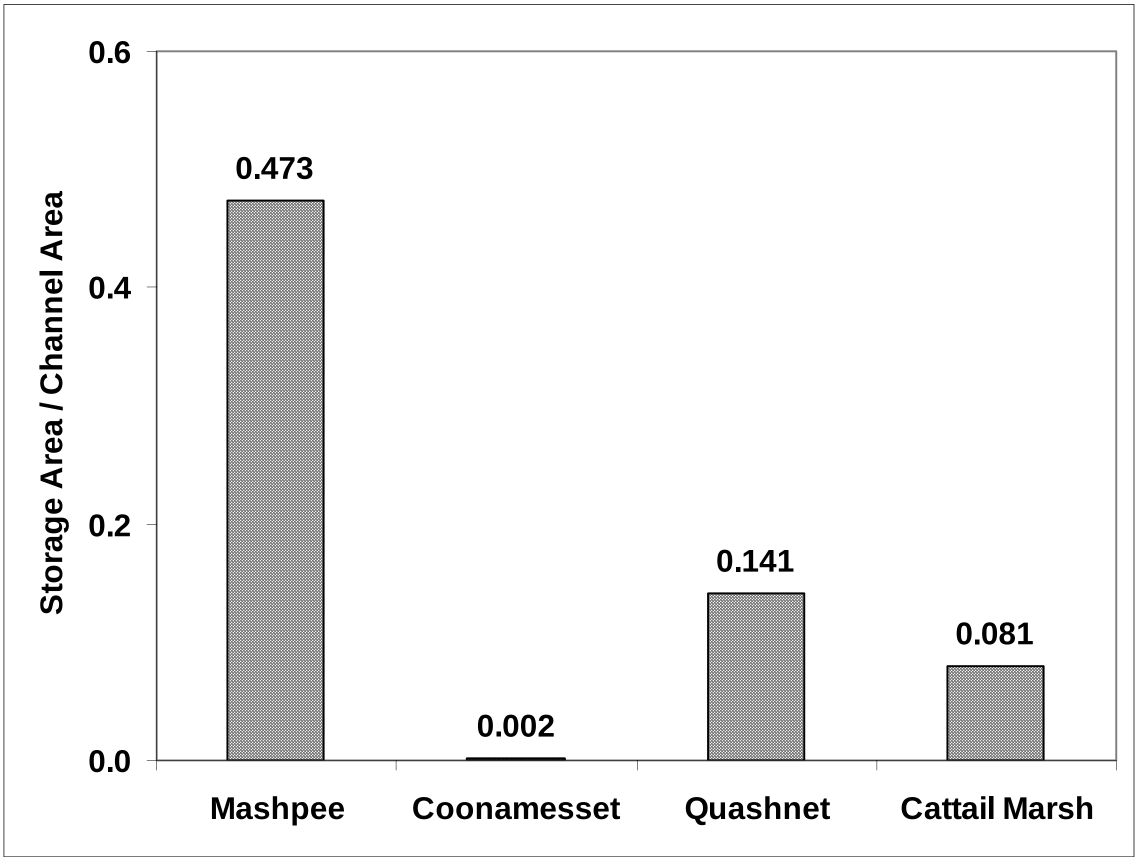

Figure 7. Storage to channel area ratios

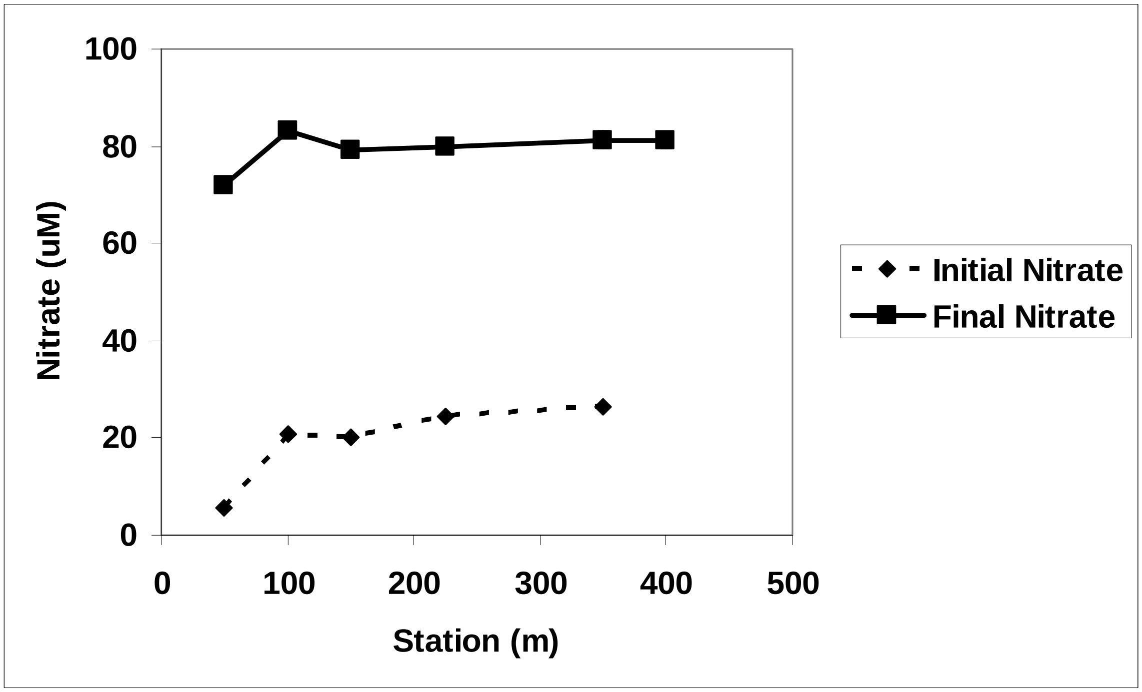

Figure 8. Mashpee nitrate concentrations before and after solute addition

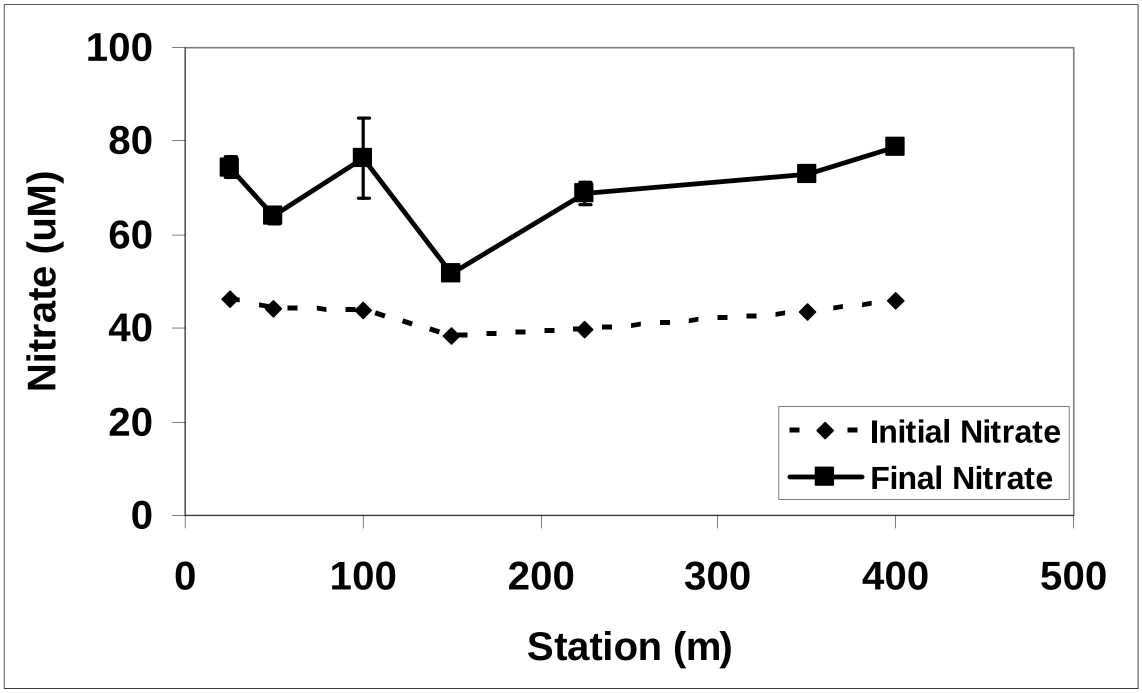

Figure 9. Coonamesset nitrate concentrations before and after solute addition

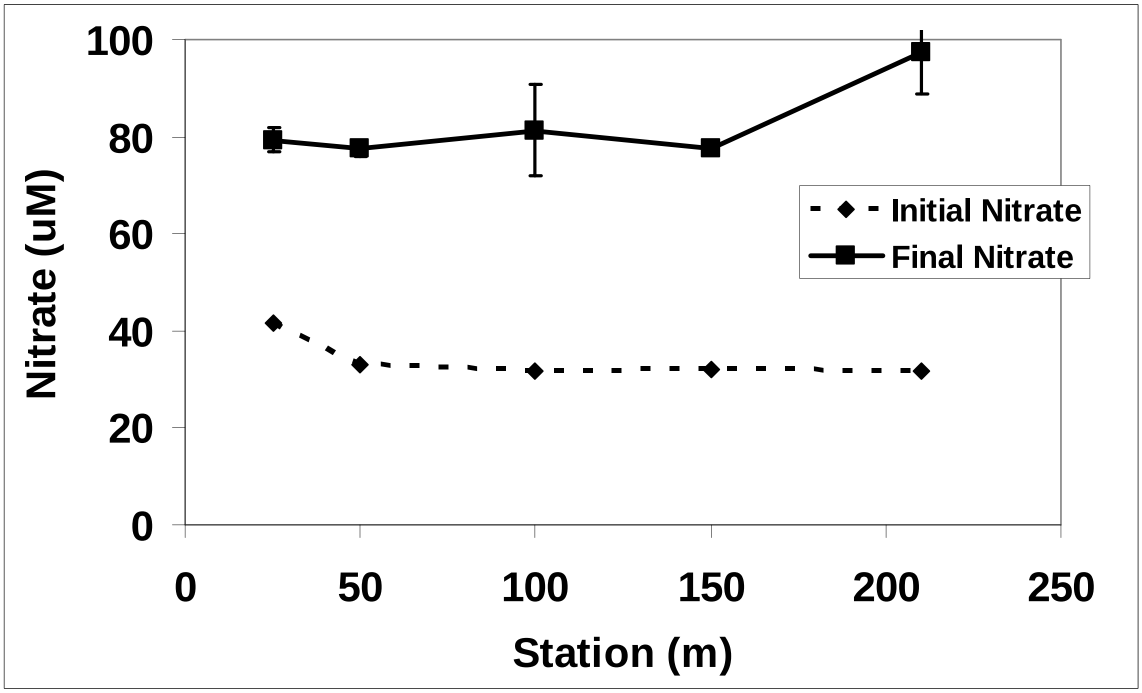

Figure 10. Cattail marsh nitrate concentrations before and after solute addition.

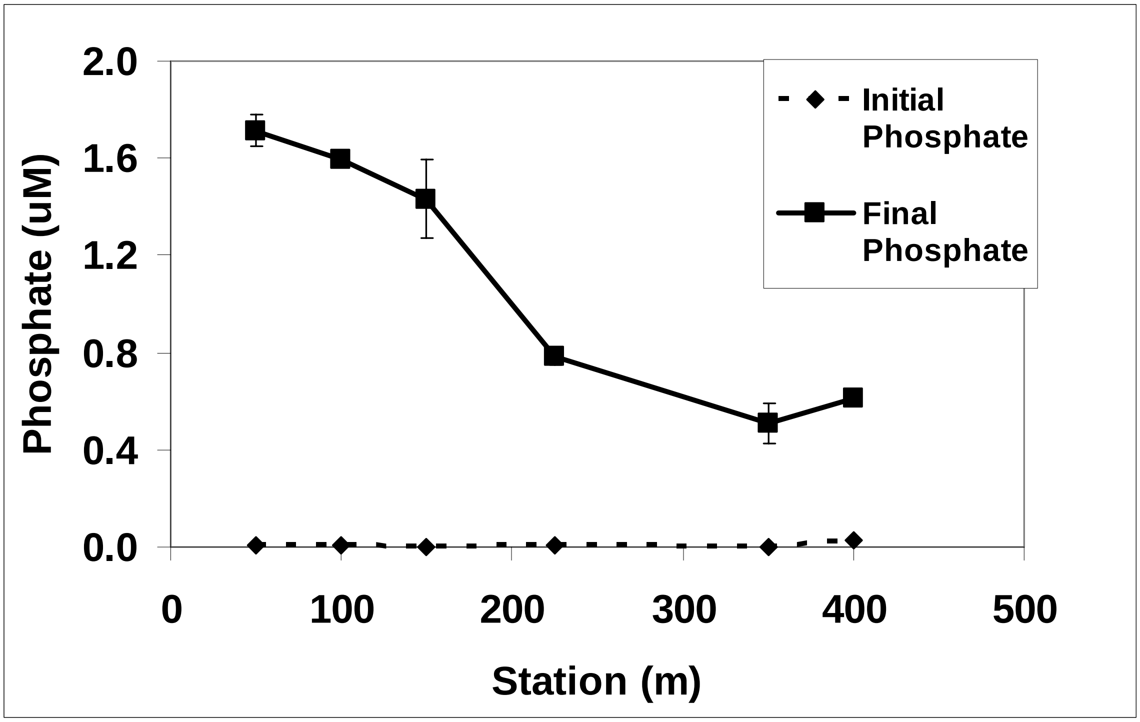

Figure 11. Mashpee phosphate concentrations before and after solute addition.

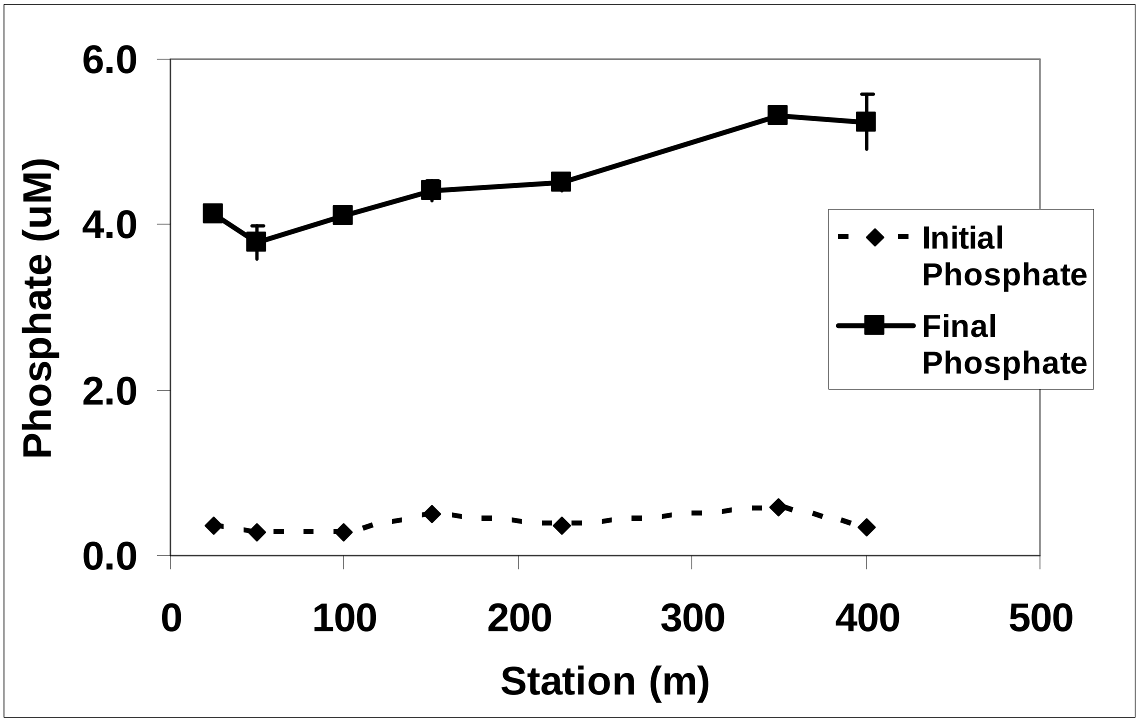

Figure 12. Coonamesset phosphate concentrations before and after solute addition

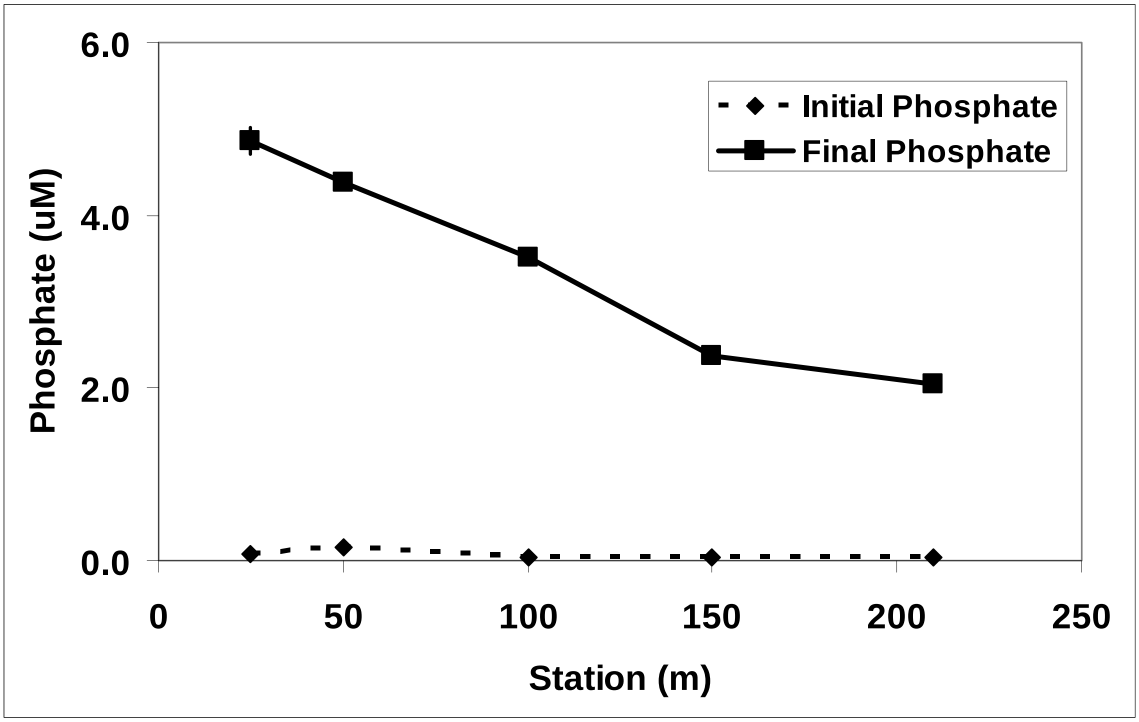

Figure 13. Cattail marsh phosphate concentrations before and after solute addition.

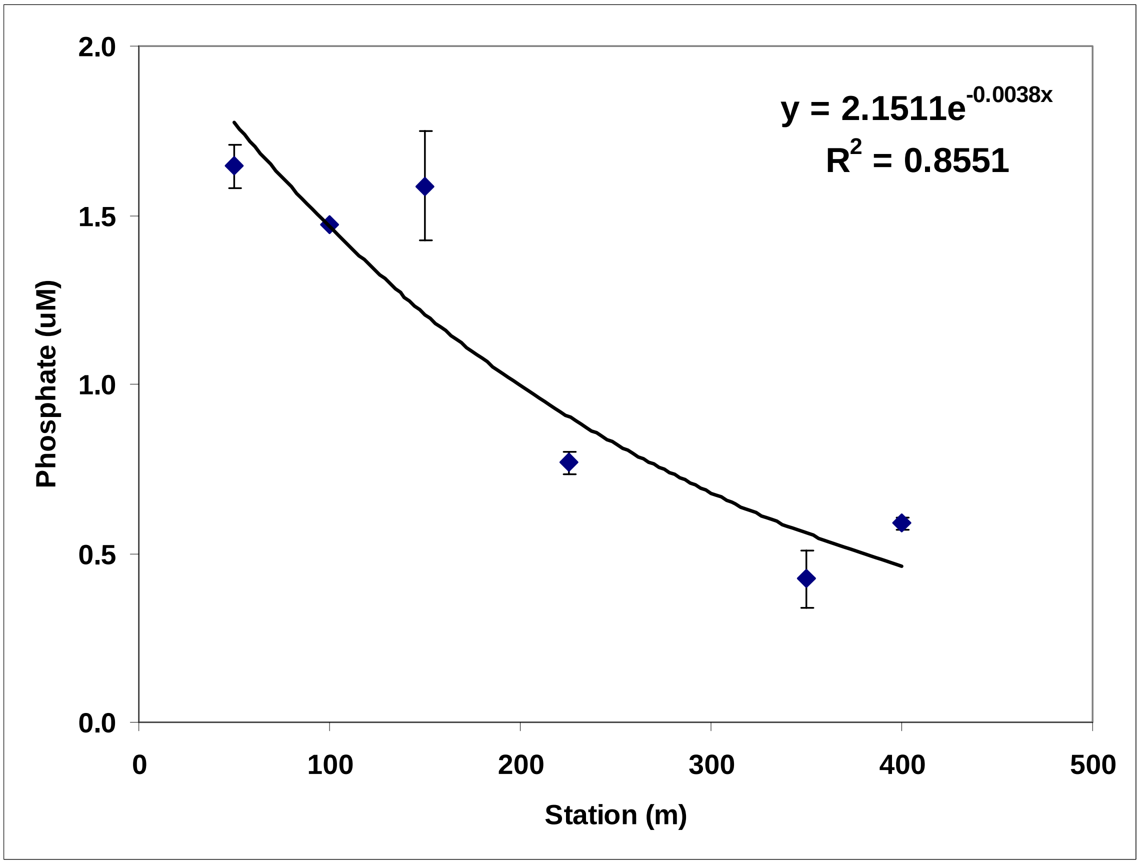

Figure 14. Phosphate concentrations in Mashpee relative to ambient levels

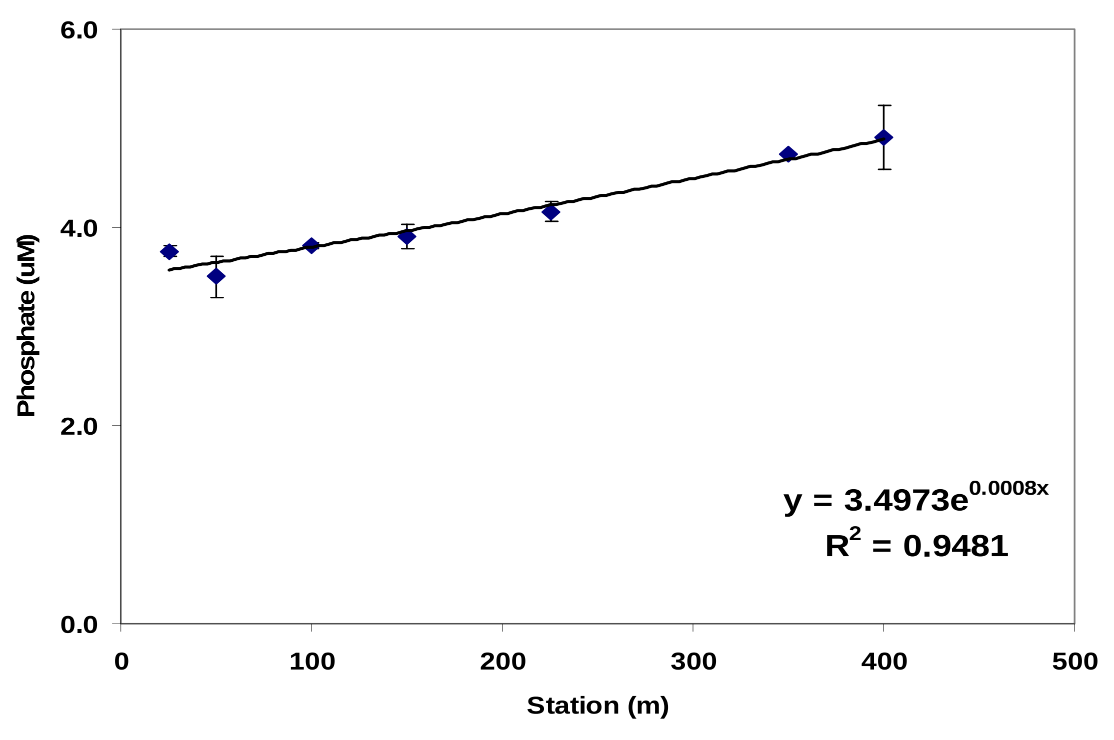

Figure 15. Phosphate concentrations in Coonamesset relative to ambient levels

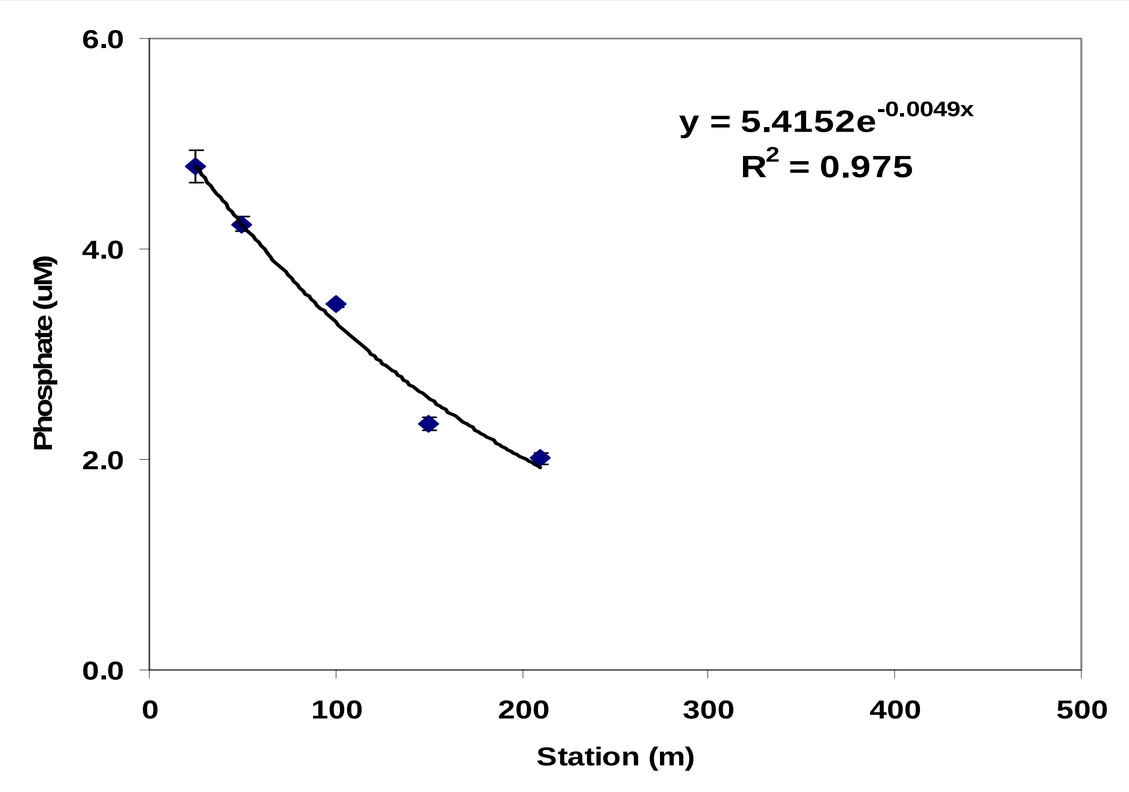

Figure 16. Phosphate concentrations in cattail marsh relative to ambient levels.

Table 3. Phosphate uptake rates and lengths

RIVER	**PHOSPHATE UPTAKE RATE**	**UPTAKE LENGTH**
	(m^{-1})	**(m)**
Mashpee	0.0038	263
Coonamesset	0	infinity
Cattail Marsh	0.0049	204

Table 4. Summary of nutrient addition data

Mashpee

Station	Nitrate Initial	Nitrate Final	Standard Deviation	Phosphate Initial	Phosphate Final	Standard Deviation	Chloride
(m)	(uM)	(uM)		(uM)	(uM)		(mg/L)
50	5.75	71.81	0.585	0.004	1.71	0.065	57.31
100	20.69	83.14	0.760	0.005	1.59	0.000	84.78
150	20.18	79.07	0.310	0.003	1.43	0.161	57.86
225	24.45	80.02	0.940	0.004	0.78	0.032	56.45
350	26.28	81.26	1.855	0.003	0.51	0.083	362.6
400		81.06	1.461	0.027	0.61	0.018	60.69

Coonamesset

Station	Nitrate Initial	Nitrate Final	Standard Deviation	Phosphate Initial	Phosphate Final	Standard Deviation	Chloride
(m)	(uM)	(uM)		(uM)	(uM)		(mg/L)
25	46.27	74.45	2.305	0.367	4.13	0.053	428.9
50	44.34	63.91	1.665	0.282	3.78	0.205	44.58
100	44.01	76.41	8.540	0.289	4.10	0.028	44.68
150	38.31	51.86	0.020	0.501	4.41	0.127	47.69
225	39.77	68.84	2.520	0.353	4.51	0.099	103.93
350	43.43	73.08	0.630	0.579	5.32	0.000	53.09
400	45.98	78.71	1.099	0.335	5.24	0.325	46.68

Cattail Marsh

Station	Nitrate Initial	Nitrate Final	Standard Deviation	Phosphate Initial	Phosphate Final	Standard Deviation	Chloride
(m)	(uM)	(uM)		(uM)	(uM)		(mg/L)
25	41.63	79.32	2.500	0.076	4.86	0.157257	52.14
50	32.86	77.41	1.550	0.150	4.39	0.076092	56.7
100	31.59	81.30	9.380	0.038	3.51	0.025364	54.98
150	31.86	77.54	0.620	0.038	2.38	0.060874	54.5
210	31.55	97.31	8.590	0.036	2.04	0.050728	55.88

Table 5. Summary of streambed assessment

	% Cover	% Possible Transient Storage	% Vegetation
Mashpee	83	83	49
Coonamesset	13	32	13
Quashnet	50	49	19

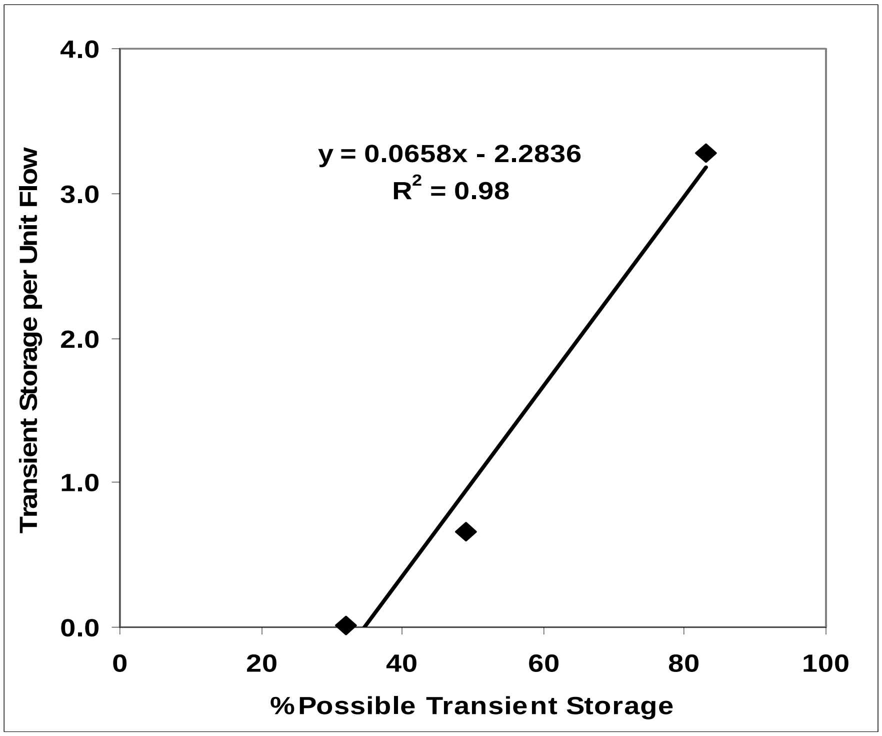

Figure 17. Possible transient storage vs. storage/flow ratio

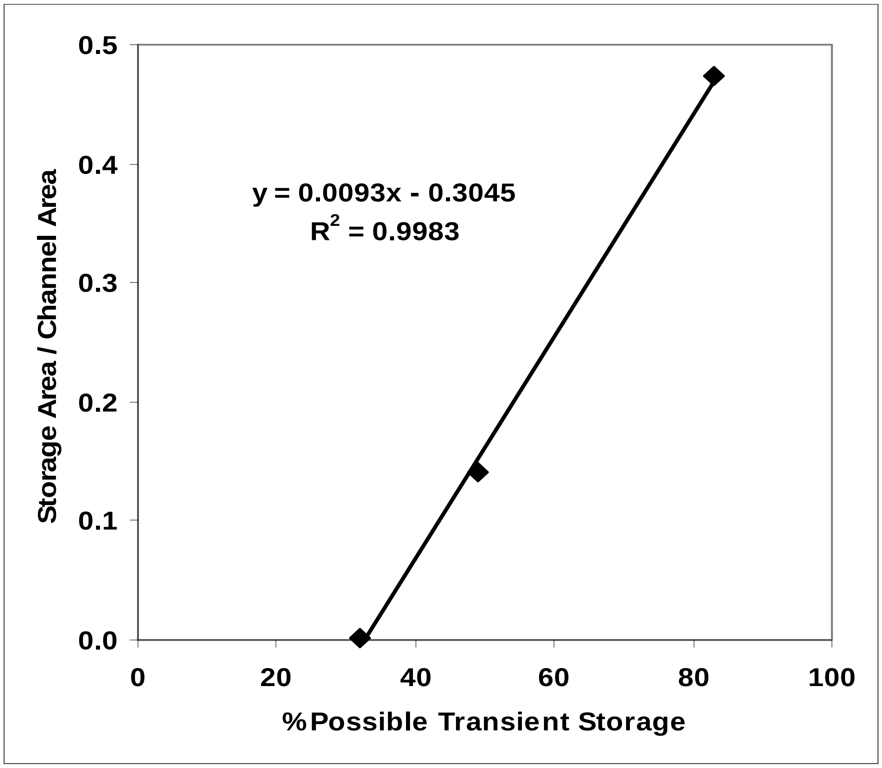

Figure 18. Possible transient storage vs. storage/channel ratio

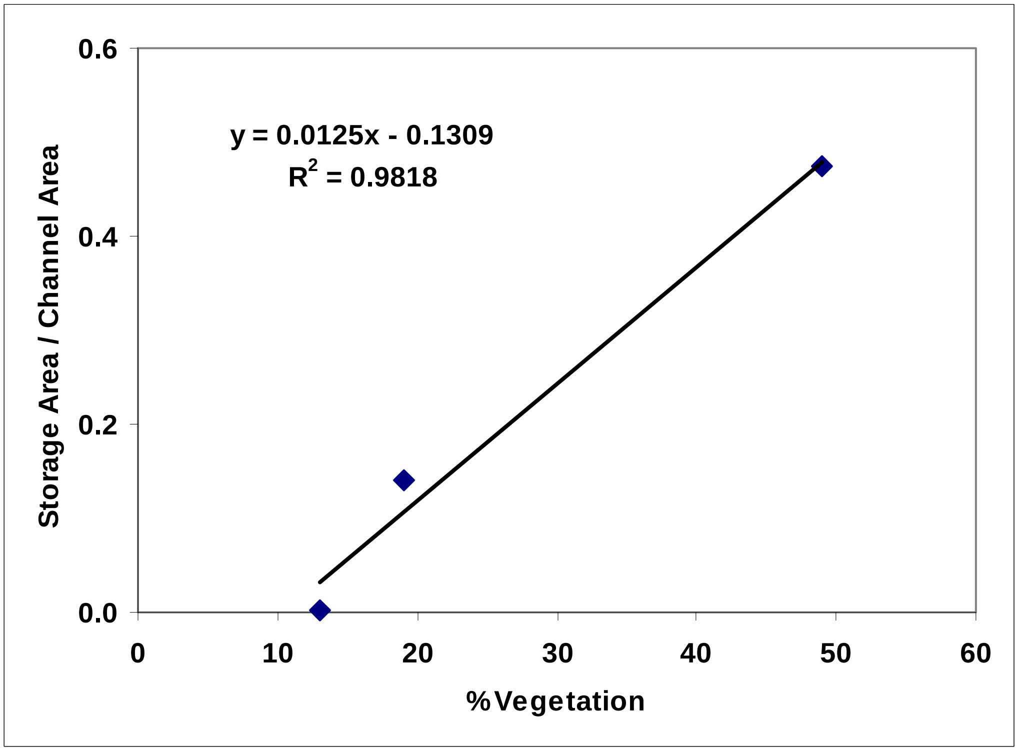

Figure 19. Streambottom vegetation vs. storage/channel ratio

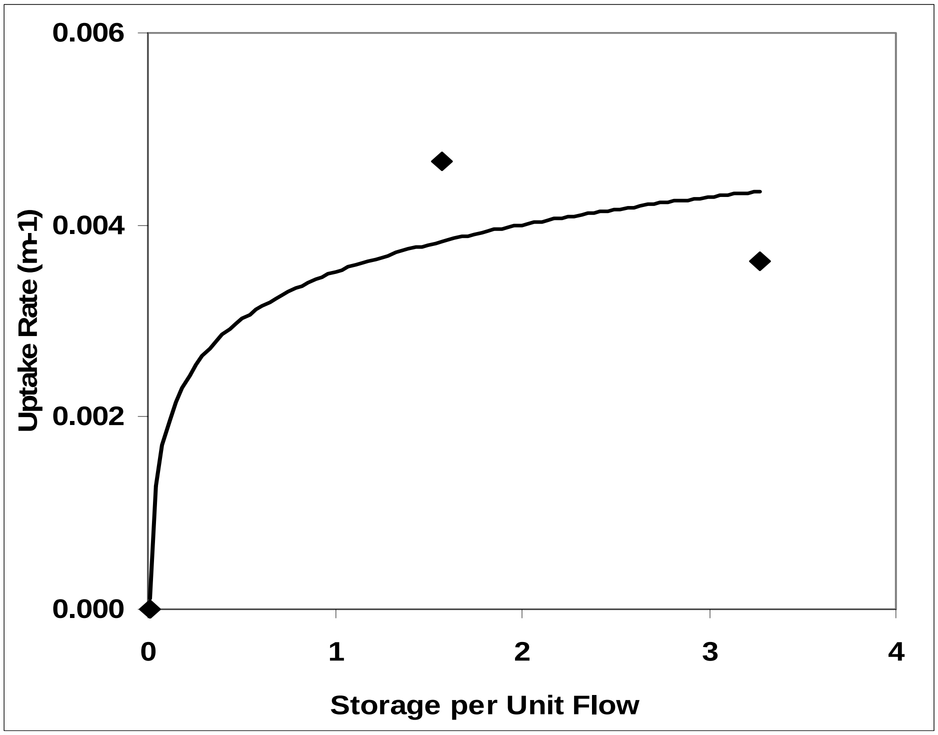

Figure 20. Relationship of storage/flow ratio and phosphate uptake rates

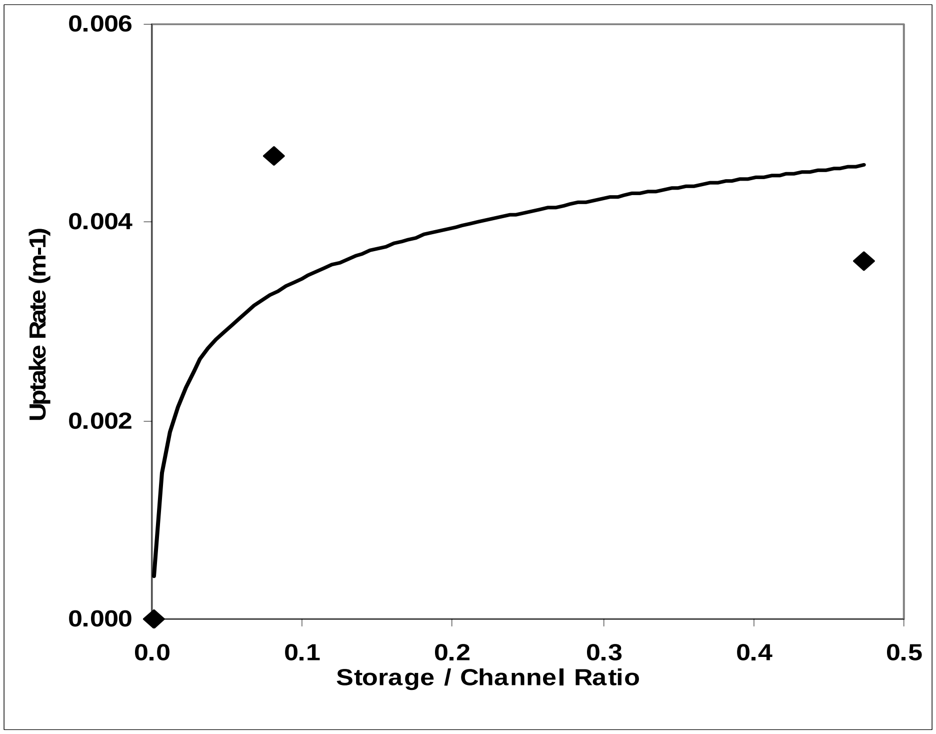

Figure 21. Relationship of storage/channel area to phosphate uptake rates

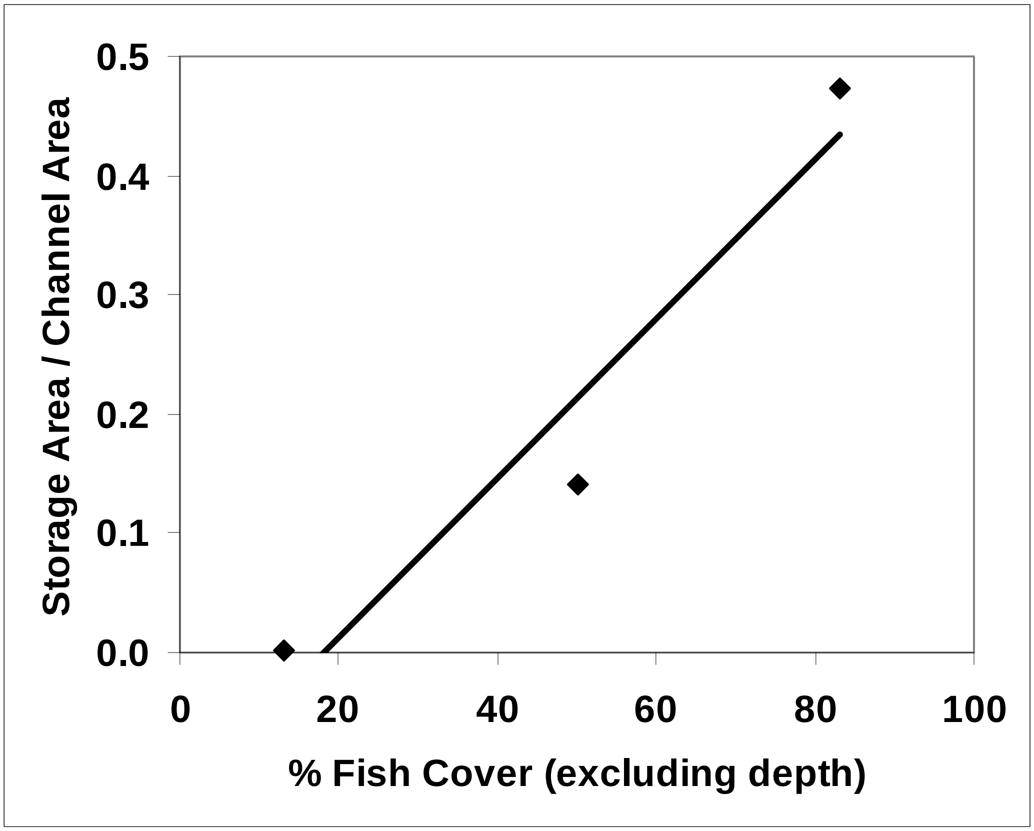

Figure 22. Relationship of fish cover to transient storage