Analysis of loadings

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1 Goal

Stream health is threatened by high sediment and phosphorus loads, which are carried into the streams by runoff from the surrounding landscape. It has been shown previously[1] that the phosphorus and sediment loads in Wisconsin are not evenly distributed in time - rather, most of the annual loading arrives during two pulses: one in early spring, associated with the melting of the winter snowpack, and the other in midsummer, at the same time as the most intense summer thunderstorms. In this study, we define loading "events" that can span multiple days of continuous runoff. Our goal is to then characterize the events that produce the greatest loading, in order to inform management practices that aim to improve stream health by reducing sediment and phosphorus loads.

2 Data

Description The data in this report comes from eight Wisconsin streams that were monitored (with some gaps in data collection) between 1989 and 2009. The streams and the period during which each was monitored are:

Stream	Events	Years
Eagle	429	1991-1994, 2003-2007
Joos Valley	473	1990-1994, 2002-2007
Otter	424	1990-1997, 2000-2002
Brewery	670	1985, 1990-1998, 2000-2001
Garfoot	527	1985, 1990-1993, 1995-1998
Kuenster	218	1992-1995
Rattlesnake	170	1991-1994
Bower	373	1990-1994, 2006-2009

Each entry in our data set represents one loading event, which is defined based on the hydrograph - the event begins when the loading rises from a base level toward a peak, and ends when the loading falls back to its new base level. Two kinds of load are measured for each event - the sediment load and the phosphorus load. There are two typical ways that sediment and phosphorus get into streams: they can be carried by runoff during a rainstorm or by melting snow. The load from each event can be divided into two components: the base flow component and the storm flow component. The two components refer, respectively, to the load carried by the stream's underlying base flow and to that carried by the additional stormwater pulse.

The phosphorus loading was not measured at Brewery Creek from October 1999 onward.

Not all of the data can be collected for each event. For instance, rainfall is measured only when the ground is free of snow, because snow interferes with the rain gauges. And the amount of snowmelt is estimated by multiplying the snow's water content by the change in snow depth during a warm snap, which is inaccurate when additional snow falls during the event. Broadly, there is one set of measurements that are made during rainfall-driven events and a different set of measurements that are made during snowmelt-driven events. Because of this, the two types of event are modeled separately.

Exploratory Analysis The first task was to determine how loads are distributed between snowmelt-driven and rainfall-driven events. The total loads from each kind of event are tabulated in Tables 1 (sediment) and 2 (phosphorus). Figure 1 presents the same information as the tables, while Figure 2 also compares the load from indivudual snowmelt- and rainfall-driven events. In general, more of the load of both phosphorus and sediment is from rainfall-driven events, but at Garfoot and Kuenster more of the both kinds of load came from snowmelt-driven events. At all sites except Garfoot and Kuenster, snowmelt-driven events contributed a larger proportion of phosphorus loading than of sediment loading (and at Garfoot and Kuenster, difference between the proportions was small.) At most sites the difference between the proportion of sediment load produced by snowmelt-driven events and the proportion of phosphorus load produced by snowmelt-driven events was less than ten percentage points, but at Bower the difference was about 34 percentage points. This suggests that melting snow carries proportionally more phosphorus than does rainfall-runoff, which might be the case if the the phosphorus is from animal poop that accumulates on fallen snow, while the sediment comes from dirt that is mainly trapped under the snowpack.

Note: initial analysis suggests that the major events are not evenly distributed, but occur more often in some years than in others. It may also be the case that the major phosphorus-loading events and the major sediment-loading events occur in different years, and that the years with more major snowmelt-driven events are not the same years as those with more rainfall-driven events. We need to test the hypotheses that there is no significant difference between years in the proportion of events that become major events. This could be done by a rank-sum test, where phosphorus- (or sediment-)loading events are ranked and then the sum of the ranks for 2007, say, is compared to what we should see under a uniform hypothesis... How to test whether the major sediment and phosphorus events occur in the same years, and whether the major snowmelt-driven and rainfall-driven events happen in the same years? I do not yet know.

We investigated dividing the snow-free seasons into early and late subseasons, separating the two on May 15th of each year. If vegetation serves to hold the soil together, and to increase both evapotranspiration and infiltration, then erosion may be more common early in the spring before most of the summer's vegetation appears. If so, the relationship between rainfall and the stream's loading might change during the summer.

The investigation was done by making linear models to describe the sediment and phosphorus loading during the two subseasons and comparing them to a single model fit to the entire snow-free period. Because the split makes the model more flexible, it will certainly improve the model's fit - the question is whether that improvement is enough to justify making the model more complex. At all four streams, the model improvement was statistically significant but too small to matter (the split models explained about 1%-2% more of the loads). We will not use the split in the rest of the analysis.

	snowmelt-driven	rainfall-driven
Eagle	27.0%	73.0%
Joos	26.9%	73.1%
Otter	35.4%	64.6%
Brewery	32.8%	67.2%
Garfoot	55.6%	44.4%
Kuenster	68.5%	31.5%
Rattlesnake	48.9%	51.1%
Bower	28.8%	71.2%

Table 1 – Proportion of total suspended solids loading contributed by each type of event

Over the course of the monitoring period, the majority of the total load (both of sediment and of phosphorus) was carried during just a few major events. Just 10% of the events carried between 73.1% (at Otter) and 97.1% (at Bower) of the total sediment load; the same events produced between 64.6% (at Otter) and 88% (at Joos) of the total phosphorus load.

	snowmelt-driven	rainfall-driven
Eagle	32.8%	67.2%
Joos	36.4%	63.6%
Otter	46.5%	53.5%
Brewery	49.6%	50.4%
Garfoot	55.2%	44.8%
Kuenster	61.1%	38.9%
Rattlesnake	52.6%	47.4%
Bower	62.9%	37.1%

Table 2 – Proportion of total phosphorus loading contributed by each type of event

3 Analysis

3.1 Variable selection

In order to make a model of the load carried by the stream, we need to select the predictor variables that have explanatory power. We used stepwise regression with the Bayesian Information Criterion (BIC) to screen the potential predictor variables.

Rainfall-driven events The predictors that survived the screening at each stream are listed in Table 7. The variables are listed in the order of their importance to the model.

In every case, the theisen rainfall is the most important predictor, followed usually by antecedent baseflow. Using just those two predictors results in an R^2 greater than 0.7 in most models (the exception is at Brewery Creek - see Tables 5 and 6.) Since the antecedent baseflow is considered an indicator of how wet is in the watershed before each event, we conclude that the amount of sediment and phosphorus washed into a stream by each event is mainly a function of the quantity of water in the system. At Brewery Creek, the intensity of rainfall is a more important predictor than the total quantity of rain.

Snowmelt-driven events We had less success modeling the loading produced by the snowmelt-driven events. The predictors that survived the screening process were different from stream to stream and those variables that did survive at most sites weren't always selected in the same order (like they were for the rainfall-driven events). What's more, the models for snowmelt-driven events were less accurate than for rainfall-driven events, ranging in R^2 from 0.24 to 0.53, with most in the 0.45 range.

At most sites, the most important predictor was a temperature measurement, either the maximum or the mean temperature during the loading event. The antecedent baseflow also appears to be important at most sites. It seems likely that, as in the case of rainfall-driven events, the loading is driven by the quantity of water that moves through the watershed during the event.

4 Conclusions

We have learned that we can predict the loading that will result from a storm with good accuracy, based just on the base flow before the storm and on the amount of rain that falls during the storm. Antecedent base flow is a measurement of how much water is in the watershed before a storm and any new water comes as rainfall, so it seems that the sediment and phosphorus loads are driven mainly by the quantity of water moving through the watershed. We have not yet found an accurate way to model the amount of load during a snowmelt-driven event but we have seen that the air temperature (which drives snowmelt), the antecedent base flow, and the amount of additional precipitation are important predictors for those events.

Most of the annual loading seems to be produced by a few major events. Characterizing these events will be an important step in describing the distribution of loadings and in informing management practices.

5 Next steps

There are at least two more creeks to include in the analysis. We also need to decide if there is an effective way to predict whether any given event will be one of the major events that produce most of the loading. Figures 4 and 3 make it look like the majority of the ranfall-driven loading comes from storms that drop at least two inches of rain. Mitigating the effect of large storms will probably require slowing the water's movement through the watershed - for instance, by impounding runoff before it can flow into the creeks. Our analysis will look at the frequency of big storms in order to get an idea of how quickly impounded water must be dealt with in order to be ready for the next event.

References

[1] M.E. Danz, S.R. Corsi, D.J. Graczyk, and R.T. Bannerman. Characterization of suspended solids and total phosphorus loadings from small watersheds in wisconsin. Scientific Investigations Report 2010-5039, United States Geological Survey, 2010.

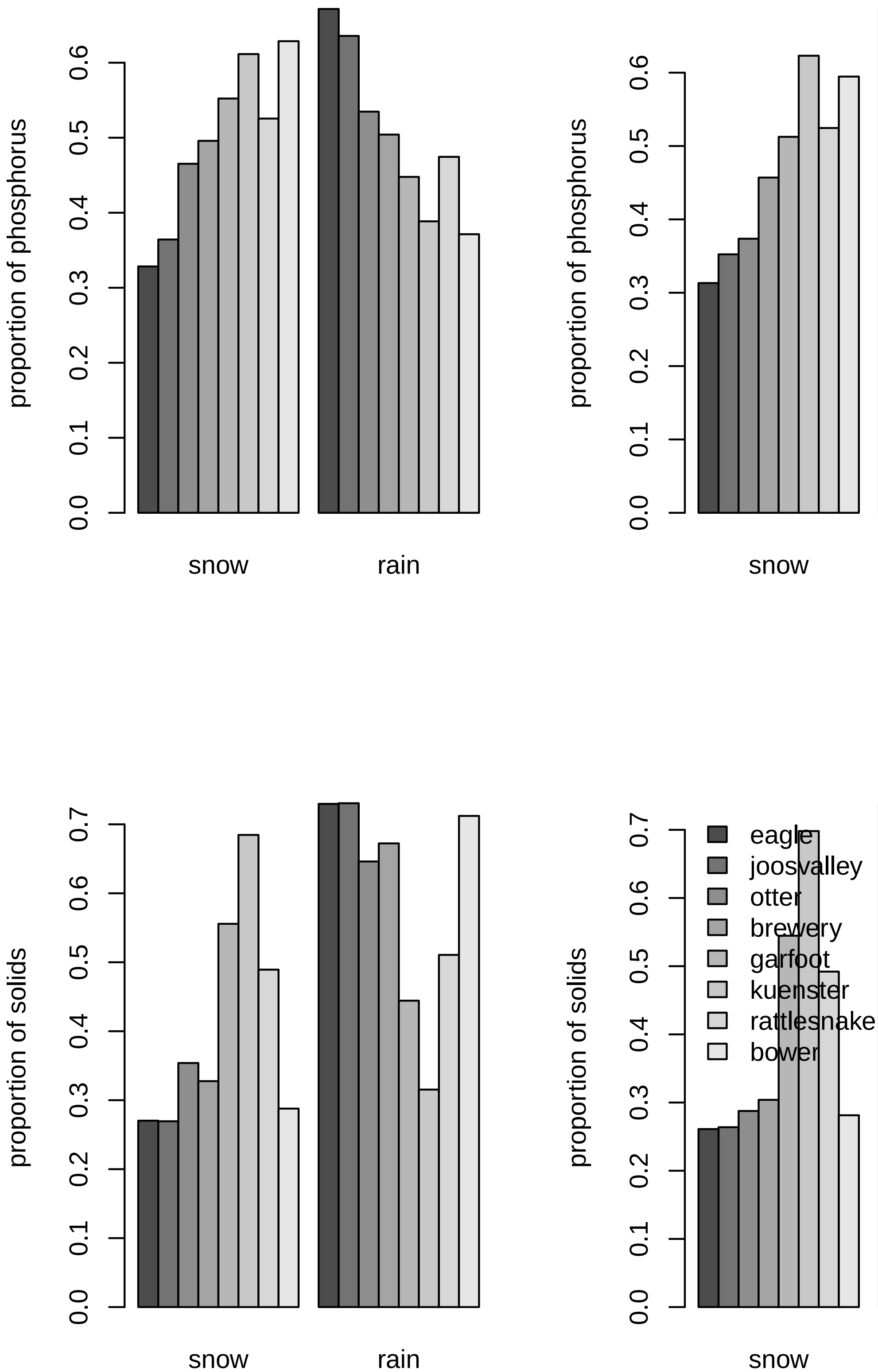

FIGURE 1 – Cumulative storm loadings at the four creeks.

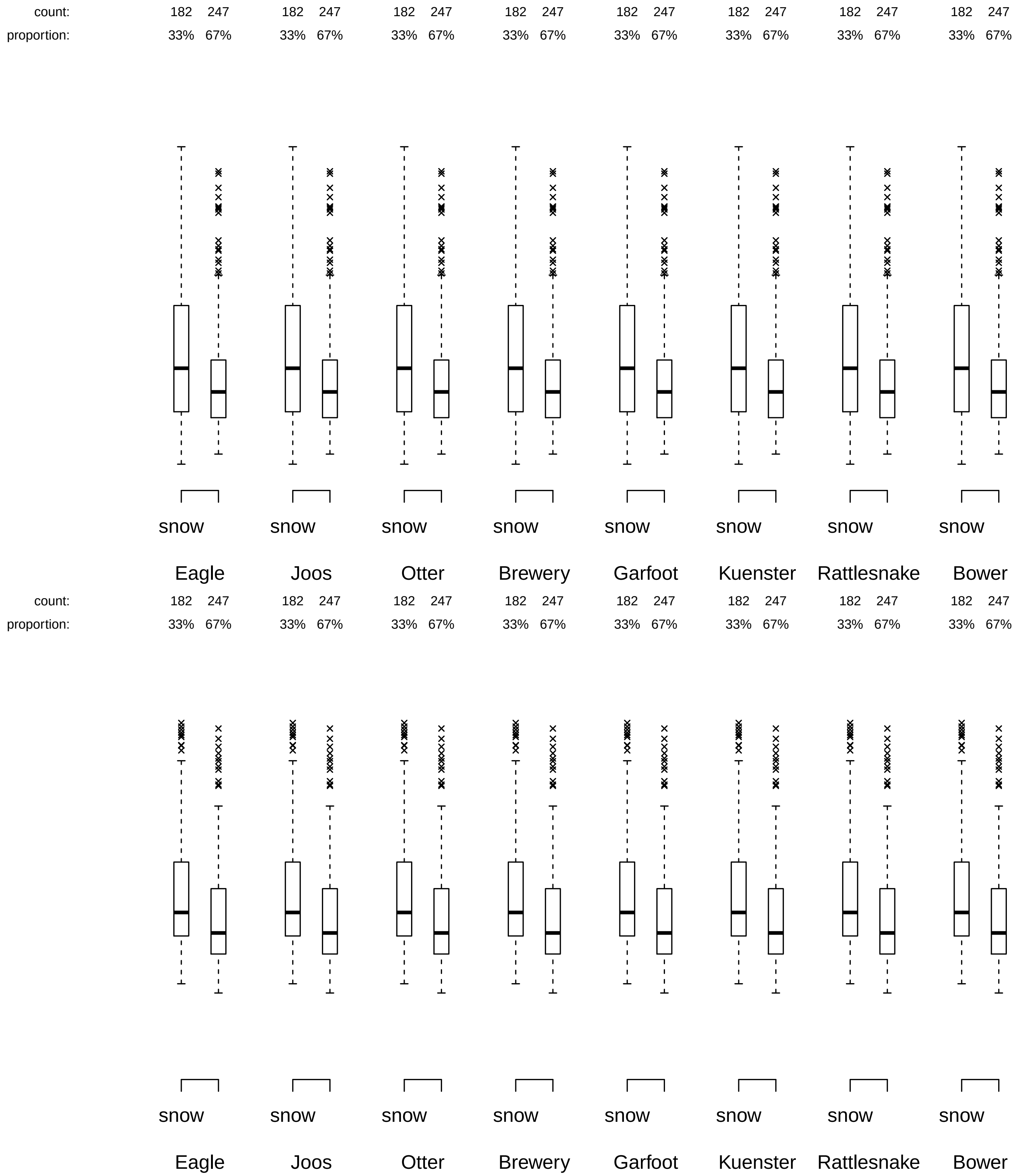

Figure 2 – Boxplots showing the sediment and phosphorus load produced by individual events at all four streams.

Sediment	R^2	Model terms
	0.515	theisen
Eagle	0.766	theisen + antecedent_qbase
	0.778	theisen + antecedent_qbase + p5max
	0.501	theisen
	0.669	theisen + antecedent_qbase
Joos	0.697	theisen + antecedent_qbase + p15max
	0.718	theisen + antecedent_qbase + p15max + ap_3day
	0.508	theisen
	0.763	theisen + antecedent_qbase
	0.784	theisen + antecedent_qbase + antecedent_tmean
Otter	0.797	theisen + antecedent_qbase + antecedent_tmean + sin_julian
	0.803	theisen + antecedent_qbase + antecedent_tmean + sin_julian + ap_5day
	0.807	theisen + antecedent_qbase + antecedent_tmean + sin_julian + ap_5day + ap_1day
	0.494	theisen
	0.715	theisen + antecedent_qbase
Brewery	0.744	theisen + antecedent_qbase + antecedent_tmean
	0.752	theisen + antecedent_qbase + antecedent_tmean + p10max
	0.444	theisen
	0.674	theisen + antecedent_qbase
Garfoot	0.687	theisen + antecedent_qbase + p30max
	0.712	theisen + antecedent_qbase + p30max + ei
	0.722	theisen + antecedent_qbase + p30max + ei + tmean
	0.408	theisen
Kuenster	0.714	theisen + antecedent_qbase
	0.466	antecedent_qbase
	0.737	antecedent_qbase + theisen
	0.762	antecedent_qbase + theisen + ap_3day
Rattlesnake	0.781	antecedent_qbase + theisen + ap_3day + ap_1day
	0.794	antecedent_qbase + theisen + ap_3day + ap_1day + ei
	0.809	antecedent_qbase + theisen + ap_3day + ap_1day + ei + p5max
	0.295	antecedent_qbase
	0.69	antecedent_qbase + theisen
Bower	0.697	antecedent_qbase + theisen + nws_prec
	0.709	antecedent_qbase + theisen + nws_prec + tmin

Table 3

Phosphorus	R^2	Model terms
Eagle	0.58	theisen
	0.783	theisen + antecedent_qbase
	0.794	theisen + antecedent_qbase + p5max
	0.801	theisen + antecedent_qbase + p5max + tmin
	0.805	theisen + antecedent_qbase + p5max + tmin + p30max
	0.81	theisen + antecedent_qbase + p5max + tmin + p30max + tmax
Joos	0.544	theisen
	0.716	theisen + antecedent_qbase
	0.733	theisen + antecedent_qbase + p15max
	0.756	theisen + antecedent_qbase + p15max + ap_3day
Otter	0.486	theisen
	0.741	theisen + antecedent_qbase
	0.766	theisen + antecedent_qbase + tmin
	0.779	theisen + antecedent_qbase + tmin + sin_julian
	0.785	theisen + antecedent_qbase + tmin + sin_julian + ap_5day
Brewery	0.609	theisen
	0.752	theisen + antecedent_qbase
Garfoot	0.545	theisen
	0.7	theisen + antecedent_qbase
	0.732	theisen + antecedent_qbase + nws_prec
	0.74	theisen + antecedent_qbase + nws_prec + ap_5day
Kuenster	0.44	theisen
	0.773	theisen + antecedent_qbase
	0.784	theisen + antecedent_qbase + ap_3day
	0.797	theisen + antecedent_qbase + ap_3day + ap_1day
Rattlesnake	0.366	theisen
	0.653	theisen + antecedent_qbase
	0.7	theisen + antecedent_qbase + ap_5day
Bower	0.289	antecedent_qbase
	0.578	antecedent_qbase + nws_prec
	0.64	antecedent_qbase + nws_prec + tmin
	0.678	antecedent_qbase + nws_prec + tmin + sin_julian
	0.708	antecedent_qbase + nws_prec + tmin + sin_julian + theisen
	0.724	antecedent_qbase + nws_prec + tmin + sin_julian + theisen + tmax
	0.729	antecedent_qbase + nws_prec + tmin + sin_julian + theisen + tmax + ap_5day

Table 4

Sediment	R^2	Model terms
	0.286	tmax
	0.403	tmax + total_water
Eagle	0.469	tmax + total_water + antecedent_qbase
	0.505	tmax + total_water + antecedent_qbase + antecedent_trange
	0.217	tmax
	0.405	tmax + total_water
Joos	0.507	tmax + total_water + antecedent_qbase
	0.554	tmax + total_water + antecedent_qbase + sin_julian
	0.584	tmax + total_water + antecedent_qbase + sin_julian + num_days
	0.262	tmax
	0.319	tmax + antecedent_qbase
Otter	0.52	tmax + antecedent_qbase + total_water
	0.531	tmax + antecedent_qbase + total_water + nws_snow
	0.561	tmax + antecedent_qbase + total_water + nws_snow + num_days
	0.163	num_days
Brewery	0.378	num_days + antecedent_qbase
	0.272	num_days
	0.451	num_days + antecedent_qbase
Garfoot	0.61	num_days + antecedent_qbase + total_water
	0.637	num_days + antecedent_qbase + total_water + nws_snow
	0.451	melt_water
Kuenster	0.56	melt_water + num_days
	0.654	melt_water + num_days + cos_julian
	0.189	num_days
Rattlesnake	0.196	num_days + antecedent_tmax
	0.422	total_water
	0.476	total_water + nws_snow
	0.56	total_water + nws_snow + antecedent_tmean
Bower	0.631	total_water + nws_snow + antecedent_tmean + num_days
	0.677	total_water + nws_snow + antecedent_tmean + num_days + nws_prec
	0.73	total_water + nws_snow + antecedent_tmean + num_days + nws_prec + antecedent_qbase

Table 5

Phosphorus	R^2	Model terms
Eagle	0.322	tmax
	0.443	tmax + total_water
	0.505	tmax + total_water + antecedent_qbase
	0.541	tmax + total_water + antecedent_qbase + antecedent_trange
Joos	0.228	tmax
	0.286	tmax + nws_prec
	0.398	tmax + nws_prec + num_days
	0.486	tmax + nws_prec + num_days + antecedent_qbase
Otter	0.29	tmax
	0.377	tmax + antecedent_qbase
	0.594	tmax + antecedent_qbase + total_water
	0.613	tmax + antecedent_qbase + total_water + nws_snow
	0.64	tmax + antecedent_qbase + total_water + nws_snow + num_days
Brewery	0.152	num_days
	0.305	num_days + antecedent_qbase
	0.35	num_days + antecedent_qbase + sin_julian
Garfoot	0.237	num_days
	0.362	num_days + antecedent_qbase
	0.504	num_days + antecedent_qbase + total_water
	0.54	num_days + antecedent_qbase + total_water + nws_snow
Kuenster	0.552	total_water
	0.669	total_water + nws_snow
Rattlesnake	0.244	num_days
	0.254	num_days + antecedent_tmax
Bower	0.36	total_water
	0.493	total_water + antecedent_tmean
	0.624	total_water + antecedent_tmean + num_days
	0.686	total_water + antecedent_tmean + num_days + antecedent_qbase
	0.708	total_water + antecedent_tmean + num_days + antecedent_qbase + tmin

Table 6

Solids	
Eagle:	theisen, antecedent_qbase, p5max
Joos:	theisen, antecedent_qbase, p15max, ap_3day
Otter:	theisen, antecedent_qbase, antecedent_tmean, sin_julian, ap_5day, ap_1day
Brewery:	theisen, antecedent_qbase, antecedent_tmean, p10max
Garfoot:	theisen, antecedent_qbase, p30max, ei, tmean
Kuenster:	theisen, antecedent_qbase
Rattlesnake:	antecedent_qbase, theisen, ap_3day, ap_1day, ei, p5max
Bower:	antecedent_qbase, theisen, nws_prec, tmin
Phosphorus	
Eagle:	theisen, antecedent_qbase, p5max, tmin, p30max, tmax
Joos:	theisen, antecedent_qbase, p15max, ap_3day
Otter:	theisen, antecedent_qbase, tmin, sin_julian, ap_5day
Brewery:	theisen, antecedent_qbase
Garfoot:	theisen, antecedent_qbase, nws_prec, ap_5day
Kuenster:	theisen, antecedent_qbase, ap_3day, ap_1day
Rattlenake:	theisen, antecedent_qbase, ap_5day
Bower:	antecedent_qbase, nws_prec, tmin, sin_julian, theisen, tmax, ap_5day

TABLE 7 – The most important variables in the models for rainfall-driven loading. The variables are ordered by their importance to the model of the load.

Solids	
Eagle:	tmax, antecedent_qbase, antecedent_trange, num_days
Joos:	tmax, num_days, antecedent_qbase, sin_julian, nws_prec, nws_snow, tmean
Otter:	tmax, antecedent_qbase, nws_prec, nws_snow, num_days
Brewery:	antecedent_qbase, num_days, nws_prec, sin_julian, cos_julian
Garfoot:	nws_prec, antecedent_qbase, num_days, nws_snow, antecedent_tmax
Kuenster:	num_days, antecedent_qbase
Rattlesnake:	num_days, antecedent_qbase, nws_prec
Bower:	nws_prec, antecedent_qbase, num_days, nws_snow
Phosphorus	
Eagle:	tmax, antecedent_qbase, num_days, nws_prec
Joos:	cos_julian, num_days, antecedent_qbase, nws_prec, nws_snow
Otter:	tmax, antecedent_qbase, nws_prec, sin_julian, num_days, nws_snow
Brewery:	antecedent_qbase, num_days, nws_prec, sin_julian, nws_snow
Garfoot:	nws_prec, num_days, antecedent_qbase, nws_snow, sin_julian, cos_julian, tmin
Kuenster:	num_days, antecedent_qbase
Rattlesnake:	num_days, antecedent_qbase, nws_prec
Bower:	tmax, nws_prec, antecedent_qbase, num_days, nws_snow

TABLE 8 – The most important variables in the models for snowmelt-driven loading. The variables are ordered by their importance to the model of the load.

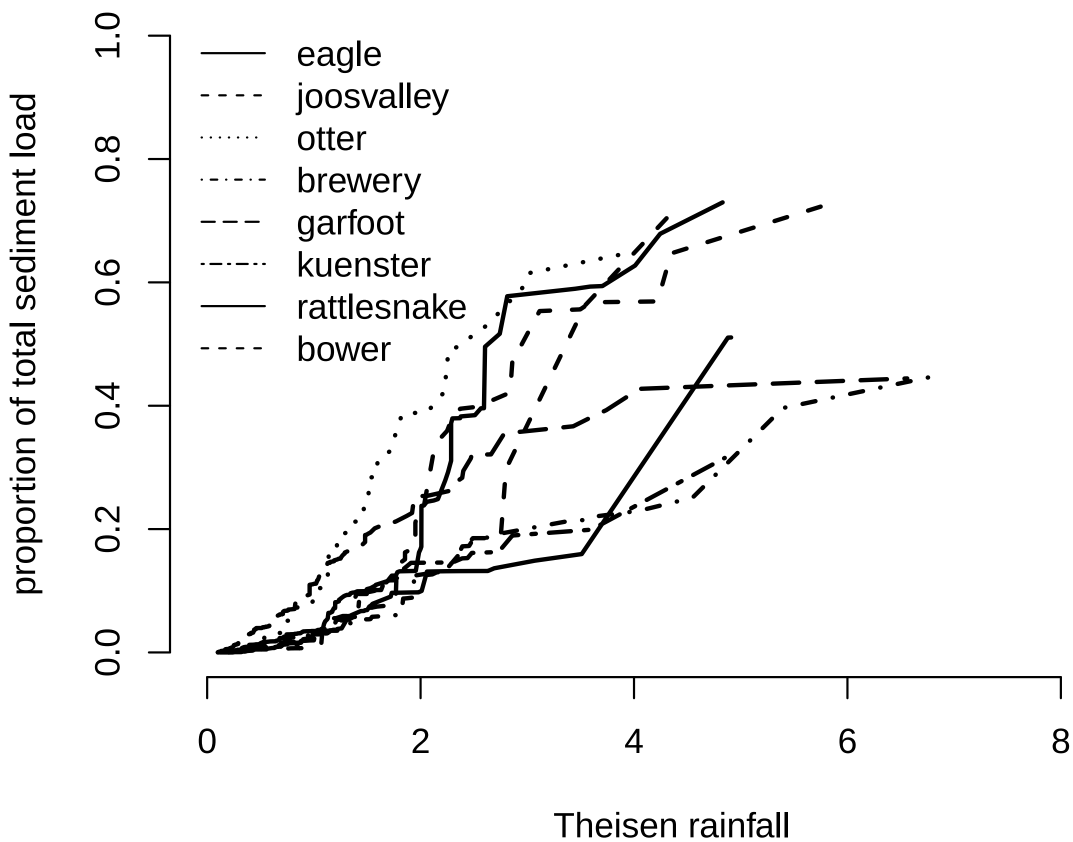

Figure 3 – Proportion of the total sediment load contributed by rainfall events up to the size shown. Snowmelt-driven events are excluded.

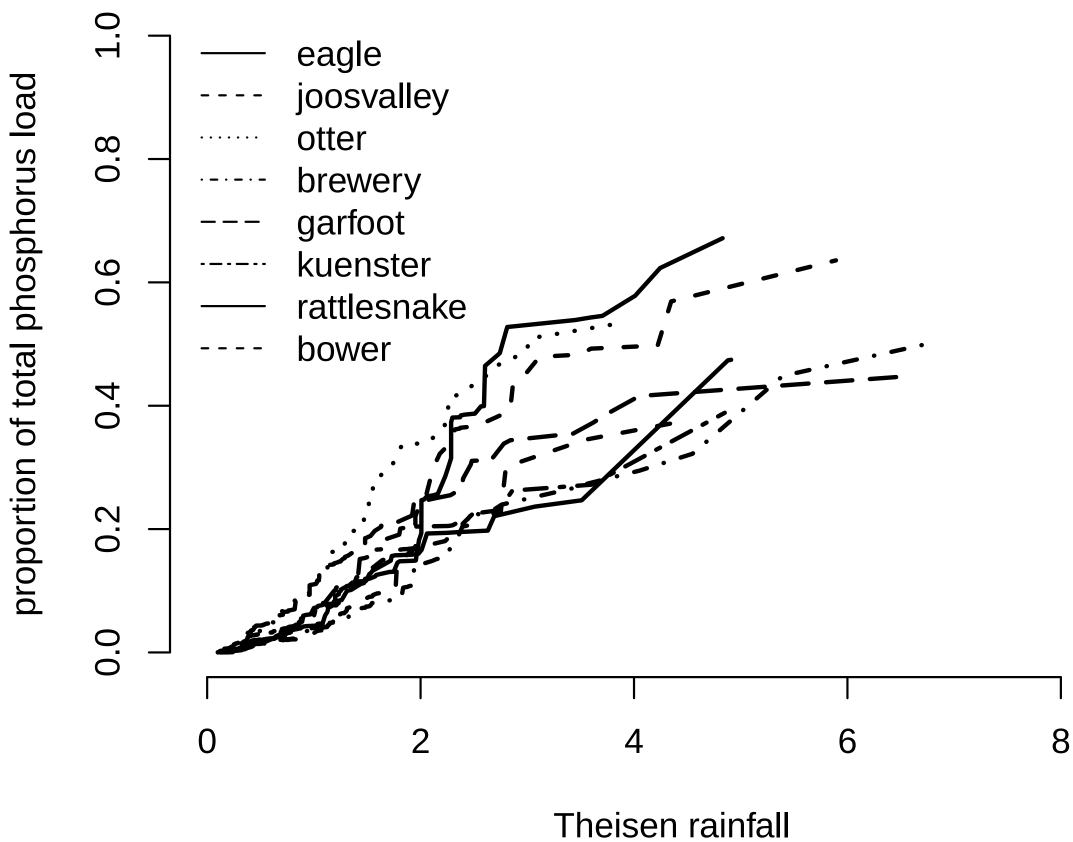

FIGURE 4 – Proportion of the total phosphorus load contributed by rainfall events up to the size shown. Snowmelt-driven events are excluded.

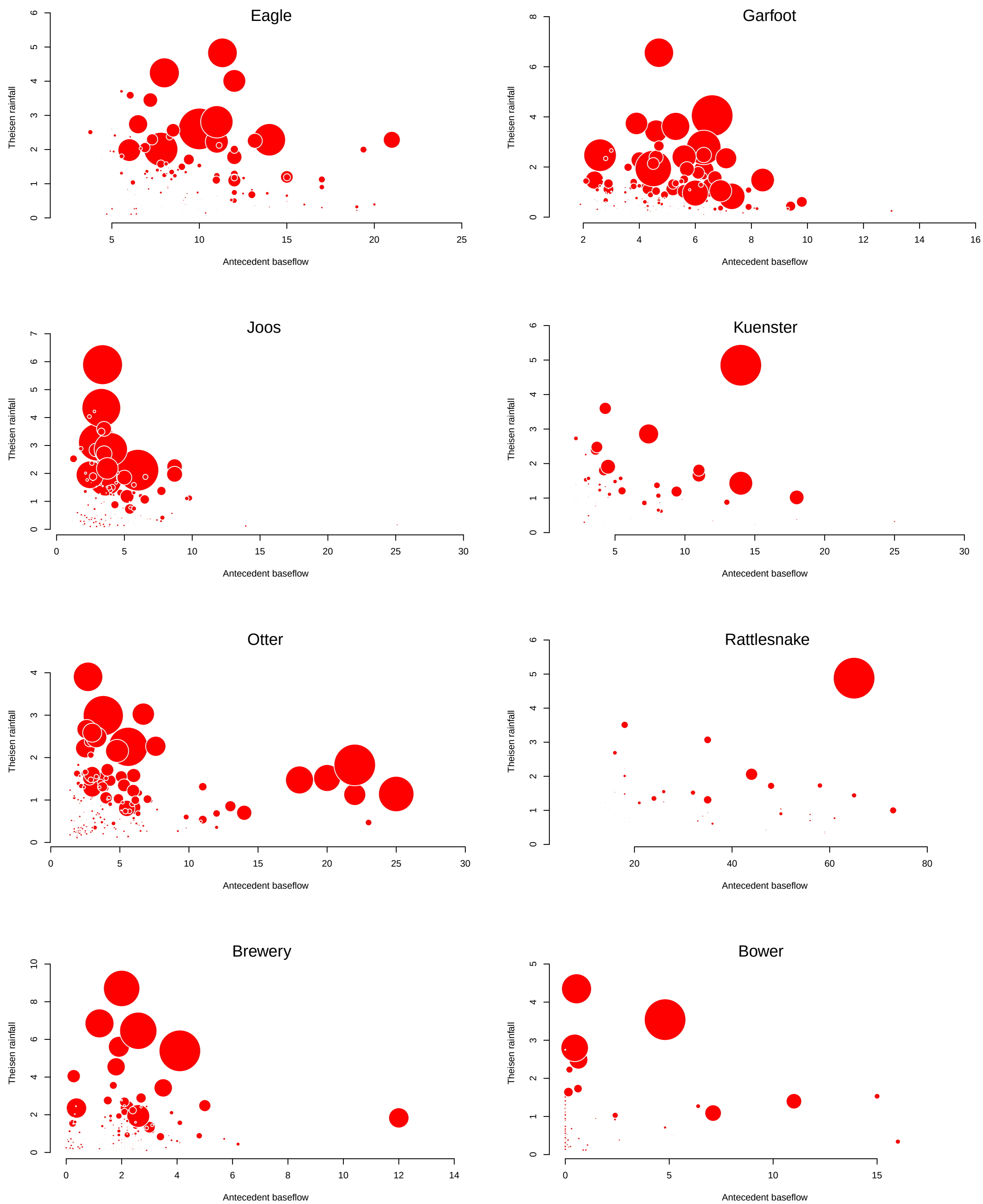

FIGURE 5 – Antecedent base flow is the horizontal axis; theisen rainfall is the vertical axis. Each dot represents one event. The size of the dot shows the total sediment load contributed by that event.