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.

Rainfall-driven events 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

Snowmelt-driven events Since sediment and phosphorus are carried into streams by runoff, it makes intuitive sense that the amount of loading during an event should depend on the amount of water that runs off during that event. In the case of rainfall-driven loading events, it is straightforward to use rain gauges to measure the amount of water entering the stream system. In the case of snowmelt-driven loading events, though, it is not easy to measure how much water melts out of the snowpack, especially when there is also additional snow falling at the same time. There is a subset of events for which we are able to estimate the amount of melting water: Those are the events when we have a measurement of the snow's water content and of the snow depth both before and after the event, and no additional snow falls during the

	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

event.

We would like to make a model that uses the available event data to describe the amount of sediment and phosphorus loading. In order to use our estimate of the snowmelt as a predictor of loading, we must ignore the snowmelt-driven events for which we cannot estimate the snowmelt. In order to determine whether that will bias our results, we first look at the overall proportion of loading that is provided by the events we will not be modeling.

We can also compare the size of events that will be ignored versus the size of events that will be modeled. The p-values of the tests comparing the sediment and phosphorus loads from each event at each stream are tabulated in table 3.

	Sediment	Phosphorus
Eagle	0.002	0.026
Joos	0.002	0.004
Otter	0.833	0.491
Brewery	0.779	0.444
Garfoot	0.573	0.157
Kuenster	0.302	0.623
Rattlesnake	0.835	0.699
Bower	0.017	0.014

Table 3 – P-values of tests of the difference in the load contributed by ignored and modeled snowmelt-driven events.

Finally, we compare the dates when the ignored events occured to the dates when the modeled events occured. The p-values for the test at each stream are tabulated in Table 4.

	p-value
Eagle	0.942
Joos	0.278
Otter	0.234
Brewery	0.591
Garfoot	0.121
Kuenster	0.169
Rattlesnake	0.047
Bower	0.443

Table 4 – P-values of tests of the difference in the date of modeled snowmelt-driven events compared to the ignored events.

It looks like the model results won't be badly biased by ignoring the events for which we don't have an estimate of the snowmelt.

Major events 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.

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 9. 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 7 and 8.) 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.

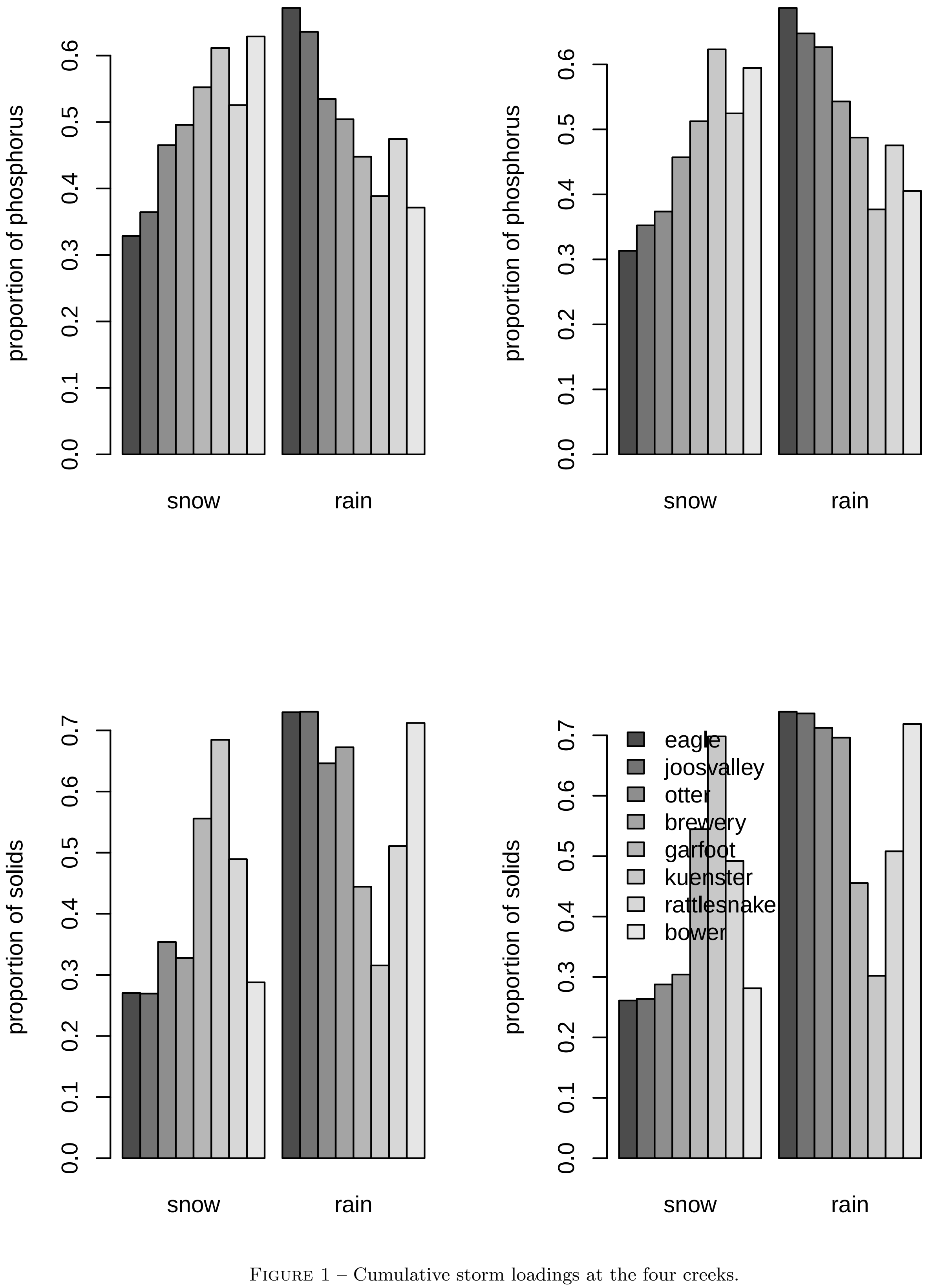

Figure 1 – Cumulative storm loadings at the four creeks.

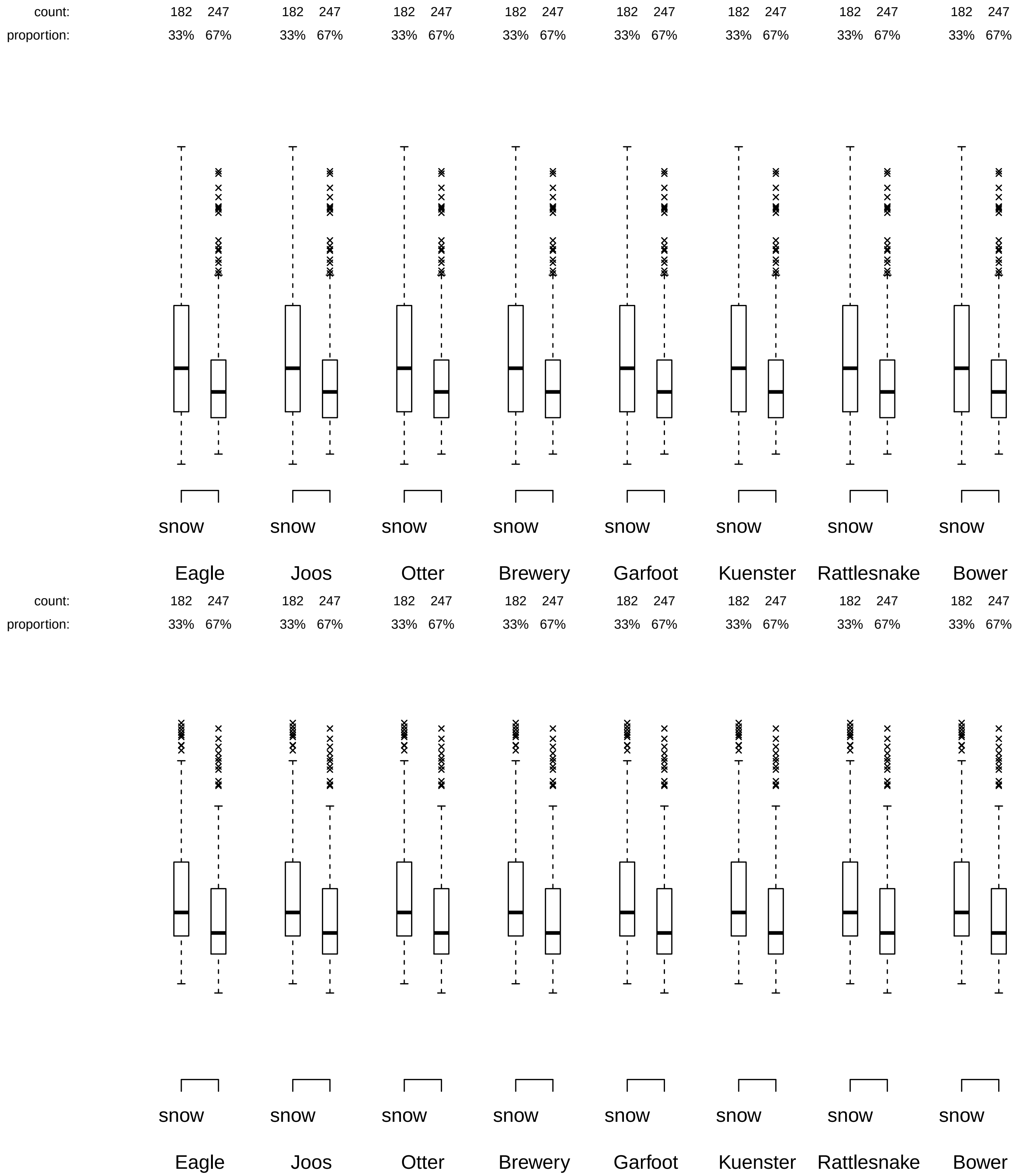

Figure 2 – Boxplots showing the sediment and phosphorus load produced by individual events at all four streams.

Sediment	R^2	Model terms
Eagle	0.515	theisen
	0.766	theisen + antecedent_qbase
	0.778	theisen + antecedent_qbase + p5max
	0.795	theisen + antecedent_qbase + p5max + antecedent_qbase_quantile
	0.799	theisen + antecedent_qbase + p5max + antecedent_qbase_quantile + duration
	0.828	theisen + antecedent_qbase + p5max + antecedent_qbase_quantile + duration + ap_1day
	0.832	theisen + antecedent_qbase + p5max + antecedent_qbase_quantile + duration + ap_1day + p30max
Joos	0.501	theisen
	0.718	theisen + antecedent_qbase_quantile
	0.745	theisen + antecedent_qbase_quantile + p15max
	0.755	theisen + antecedent_qbase_quantile + p15max + ap_3day
	0.767	theisen + antecedent_qbase_quantile + p15max + ap_3day + antecedent_qbase
Otter	0.508	theisen
	0.798	theisen + antecedent_qbase_quantile
	0.819	theisen + antecedent_qbase_quantile + antecedent_qbase
	0.826	theisen + antecedent_qbase_quantile + antecedent_qbase + ap_1day
Brewery	0.494	theisen
	0.715	theisen + antecedent_qbase
	0.744	theisen + antecedent_qbase + antecedent_tmean
	0.752	theisen + antecedent_qbase + antecedent_tmean + p10max
	0.763	theisen + antecedent_qbase + antecedent_tmean + p10max + antecedent_qbase_quantile
Garfoot	0.444	theisen
	0.674	theisen + antecedent_qbase
	0.687	theisen + antecedent_qbase + p30max
	0.712	theisen + antecedent_qbase + p30max + ei
	0.722	theisen + antecedent_qbase + p30max + ei + tmean
Kuenster	0.408	theisen
	0.768	theisen + antecedent_qbase_quantile
	0.779	theisen + antecedent_qbase_quantile + antecedent_qbase
Rattlesnake	0.479	antecedent_qbase_quantile
	0.759	antecedent_qbase_quantile + theisen
	0.778	antecedent_qbase_quantile + theisen + ap_5day
	0.79	antecedent_qbase_quantile + theisen + ap_5day + antecedent_qbase
	0.804	antecedent_qbase_quantile + theisen + ap_5day + antecedent_qbase + ap_1day
Bower	0.295	antecedent_qbase
	0.69	antecedent_qbase + theisen
	0.747	antecedent_qbase + theisen + antecedent_qbase_quantile
	0.75	antecedent_qbase + theisen + antecedent_qbase_quantile + nws_prec

Table 5

Phosphorus	R^2	Model terms
	0.58	theisen
	0.783	theisen + antecedent_qbase
	0.794	theisen + antecedent_qbase + p5max
Eagle	0.801	theisen + antecedent_qbase + p5max + tmin
	0.805	theisen + antecedent_qbase + p5max + tmin + p30max
	0.81	theisen + antecedent_qbase + p5max + tmin + p30max + tmax
	0.544	theisen
	0.747	theisen + antecedent_qbase_quantile
Joos	0.764	theisen + antecedent_qbase_quantile + p15max
	0.776	theisen + antecedent_qbase_quantile + p15max + ap_3day
	0.793	theisen + antecedent_qbase_quantile + p15max + ap_3day + antecedent_qbase
	0.486	theisen
	0.801	theisen + antecedent_qbase_quantile
Otter	0.815	theisen + antecedent_qbase_quantile + antecedent_qbase
	0.819	theisen + antecedent_qbase_quantile + antecedent_qbase + nws_prec
	0.609	theisen
Brewery	0.752	theisen + antecedent_qbase
	0.545	theisen
	0.7	theisen + antecedent_qbase
Garfoot	0.732	theisen + antecedent_qbase + nws_prec
	0.74	theisen + antecedent_qbase + nws_prec + ap_5day
	0.44	theisen
	0.773	theisen + antecedent_qbase
	0.8	theisen + antecedent_qbase + antecedent_qbase_quantile
Kuenster	0.818	theisen + antecedent_qbase + antecedent_qbase_quantile + ap_3day
	0.827	theisen + antecedent_qbase + antecedent_qbase_quantile + ap_3day + ei
	0.84	theisen + antecedent_qbase + antecedent_qbase_quantile + ap_3day + ei + p10max
	0.847	theisen + antecedent_qbase + antecedent_qbase_quantile + ap_3day + ei + p10max + p60max
	0.366	theisen
Rattlesnake	0.653	theisen + antecedent_qbase
	0.7	theisen + antecedent_qbase + ap_5day
	0.517	antecedent_qbase_quantile
	0.757	antecedent_qbase_quantile + nws_prec
	0.789	antecedent_qbase_quantile + nws_prec + theisen
Bower	0.811	antecedent_qbase_quantile + nws_prec + theisen + tmin
	0.821	antecedent_qbase_quantile + nws_prec + theisen + tmin + tmean
	0.826	antecedent_qbase_quantile + nws_prec + theisen + tmin + tmean + ap_5day

TABLE 6

Sediment	R^2	Model terms
Eagle	0.246	antecedent_qbase_quantile
	0.4	antecedent_qbase_quantile + tmax
	0.594	antecedent_qbase_quantile + tmax + total_water
Joos	0.217	tmax
	0.405	tmax + total_water
	0.512	tmax + total_water + antecedent_qbase_quantile
	0.555	tmax + total_water + antecedent_qbase_quantile + sin_julian
	0.583	tmax + total_water + antecedent_qbase_quantile + sin_julian + num_days
Otter	0.137	antecedent_qbase
	0.367	antecedent_qbase + total_water
	0.461	antecedent_qbase + total_water + nws_snow
	0.531	antecedent_qbase + total_water + nws_snow + num_days
	0.579	antecedent_qbase + total_water + nws_snow + num_days + antecedent_qbase_quantile
Brewery	0.33	antecedent_qbase_quantile
	0.478	antecedent_qbase_quantile + num_days
Garfoot	0.272	num_days
	0.451	num_days + antecedent_qbase
	0.61	num_days + antecedent_qbase + total_water
	0.637	num_days + antecedent_qbase + total_water + nws_snow
	0.668	num_days + antecedent_qbase + total_water + nws_snow + antecedent_qbase_quantile
Kuenster	0.451	melt_water
	0.56	melt_water + num_days
	0.639	melt_water + num_days + sin_julian
Rattlesnake	0.189	num_days
	0.196	num_days + antecedent_tmax
	0.197	num_days + antecedent_tmax + cos_julian
Bower	0.422	total_water
	0.476	total_water + nws_snow
	0.56	total_water + nws_snow + antecedent_tmean
	0.631	total_water + nws_snow + antecedent_tmean + num_days
	0.689	total_water + nws_snow + antecedent_tmean + num_days + antecedent_qbase_quantile
	0.718	total_water + nws_snow + antecedent_tmean + num_days + antecedent_qbase_quantile + nws_prec

Table 7

Phosphorus	R^2	Model terms
Eagle	0.218	antecedent_qbase_quantile
	0.41	antecedent_qbase_quantile + tmax
	0.609	antecedent_qbase_quantile + tmax + total_water
Joos	0.228	tmax
	0.286	tmax + nws_prec
	0.398	tmax + nws_prec + num_days
	0.49	tmax + nws_prec + num_days + antecedent_qbase_quantile
Otter	0.181	antecedent_qbase
	0.45	antecedent_qbase + total_water
	0.544	antecedent_qbase + total_water + nws_snow
	0.609	antecedent_qbase + total_water + nws_snow + num_days
	0.65	antecedent_qbase + total_water + nws_snow + num_days + antecedent_qbase_quantile
Brewery	0.152	num_days
	0.308	num_days + antecedent_qbase_quantile
	0.34	num_days + antecedent_qbase_quantile + sin_julian
	0.419	num_days + antecedent_qbase_quantile + sin_julian + nws_prec
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
	0.257	num_days + antecedent_tmax + cos_julian
Bower	0.36	total_water
	0.553	total_water + antecedent_qbase_quantile
	0.667	total_water + antecedent_qbase_quantile + num_days
	0.754	total_water + antecedent_qbase_quantile + num_days + antecedent_tmean
	0.776	total_water + antecedent_qbase_quantile + num_days + antecedent_tmean + nws_snow

Table 8

Solids	
Eagle:	theisen, antecedent_qbase, p5max, antecedent_qbase_quantile, duration, ap_1day, p30max
Joos:	theisen, antecedent_qbase_quantile, p15max, ap_3day, antecedent_qbase
Otter:	theisen, antecedent_qbase_quantile, antecedent_qbase, ap_1day
Brewery:	theisen, antecedent_qbase, antecedent_tmean, p10max, antecedent_qbase_quantile
Garfoot:	theisen, antecedent_qbase, p30max, ei, tmean
Kuenster:	theisen, antecedent_qbase_quantile, antecedent_qbase
Rattlesnake:	antecedent_qbase_quantile, theisen, ap_5day, antecedent_qbase, ap_1day
Bower:	antecedent_qbase, theisen, antecedent_qbase_quantile, nws_prec
Phosphorus	
Eagle:	theisen, antecedent_qbase, p5max, tmin, p30max, tmax
Joos:	theisen, antecedent_qbase_quantile, p15max, ap_3day, antecedent_qbase
Otter:	theisen, antecedent_qbase_quantile, antecedent_qbase, nws_prec
Brewery:	theisen, antecedent_qbase
Garfoot:	theisen, antecedent_qbase, nws_prec, ap_5day
Kuenster:	theisen, antecedent_qbase, antecedent_qbase_quantile, ap_3day, ei, p10max, p60max
Rattlenake:	theisen, antecedent_qbase, ap_5day
Bower:	antecedent_qbase_quantile, nws_prec, theisen, tmin, tmean, ap_5day

Table 9 – 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_quantile, num_days, antecedent_trange
Joos:	tmax, num_days, antecedent_qbase_quantile, nws_prec, sin_julian, nws_snow
Otter:	tmax, antecedent_qbase, nws_prec, nws_snow, num_days
Brewery:	antecedent_qbase_quantile, num_days, nws_prec, antecedent_qbase, cos_julian, nws_snow
Garfoot:	nws_prec, antecedent_qbase_quantile, num_days, nws_snow, cos_julian, antecedent_qbase
Kuenster:	num_days, antecedent_qbase
Rattlesnake:	num_days, antecedent_qbase, nws_prec
Bower:	nws_prec, antecedent_qbase, num_days, nws_snow, antecedent_qbase_quantile, cos_julian, sin_julian
Phosphorus	
Eagle:	tmax, antecedent_qbase_quantile, num_days, nws_prec, sin_julian
Joos:	num_days, antecedent_qbase_quantile, sin_julian, nws_prec, nws_snow, tmax
Otter:	tmax, antecedent_qbase, nws_prec, num_days, nws_snow, sin_julian
Brewery:	antecedent_qbase_quantile, num_days, nws_prec, antecedent_qbase, sin_julian, nws_snow
Garfoot:	nws_prec, num_days, antecedent_qbase, nws_snow, cos_julian, tmean
Kuenster:	num_days, antecedent_qbase
Rattlesnake:	num_days, antecedent_qbase, nws_prec
Bower:	antecedent_qbase_quantile, num_days, nws_prec, nws_snow, tmin

Table 10 – The most important variables in the models for snowmelt-driven loading. The variables are ordered by their importance to the model of the load.

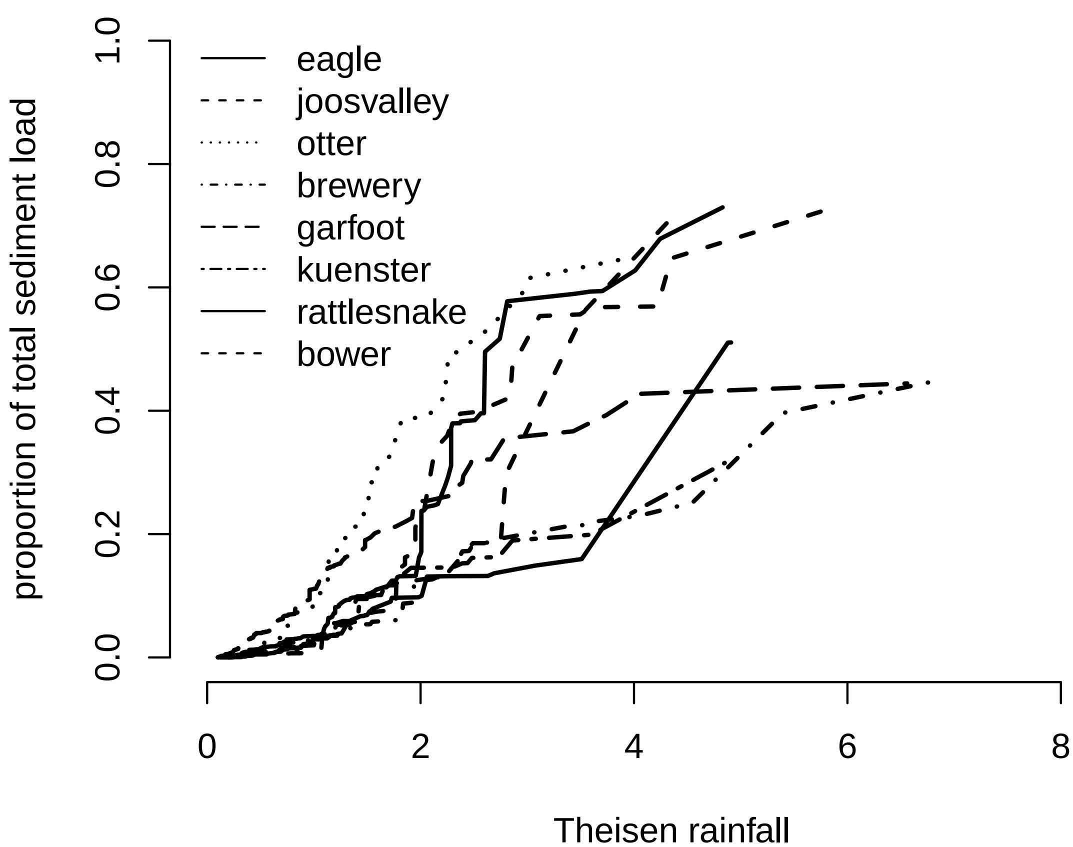

Figure 3 – Proportion of the total sediment load contributed by rainfall events up to the size shown. Snowmelt-driven events are excluded.

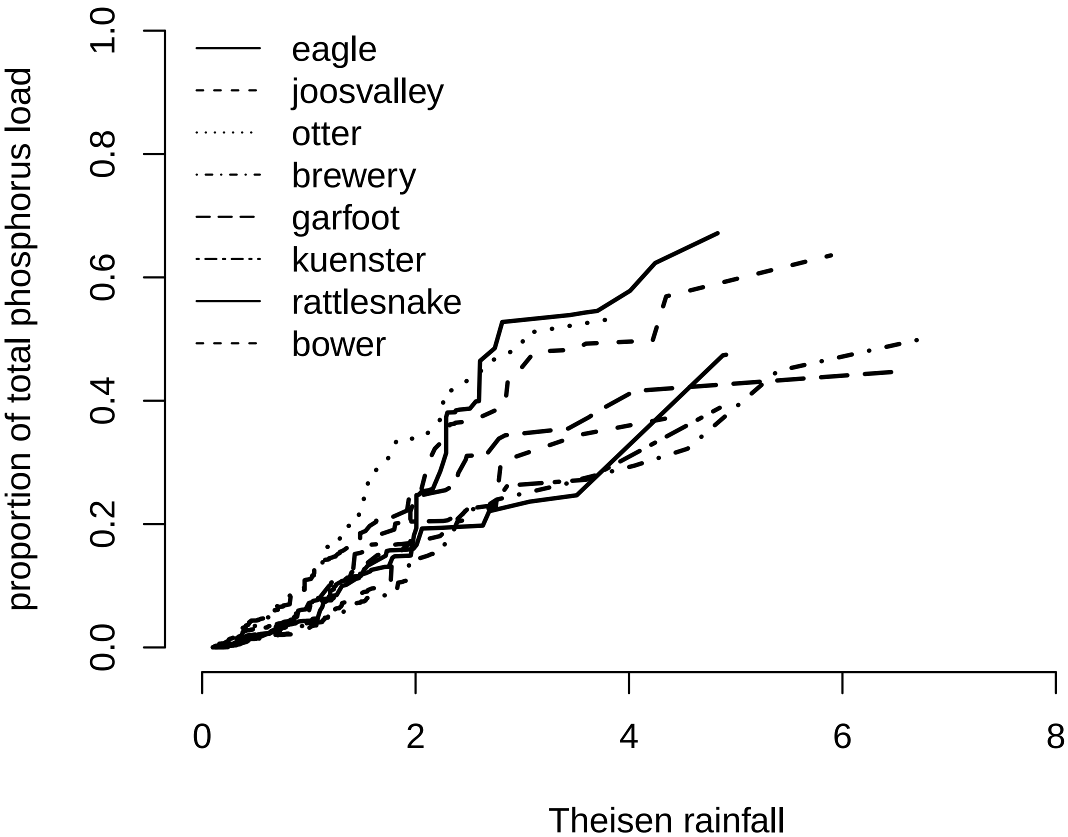

FIGURE 4 – Proportion of the total phosphorus load contributed by rainfall events up to the size shown. Snowmelt-driven events are excluded.

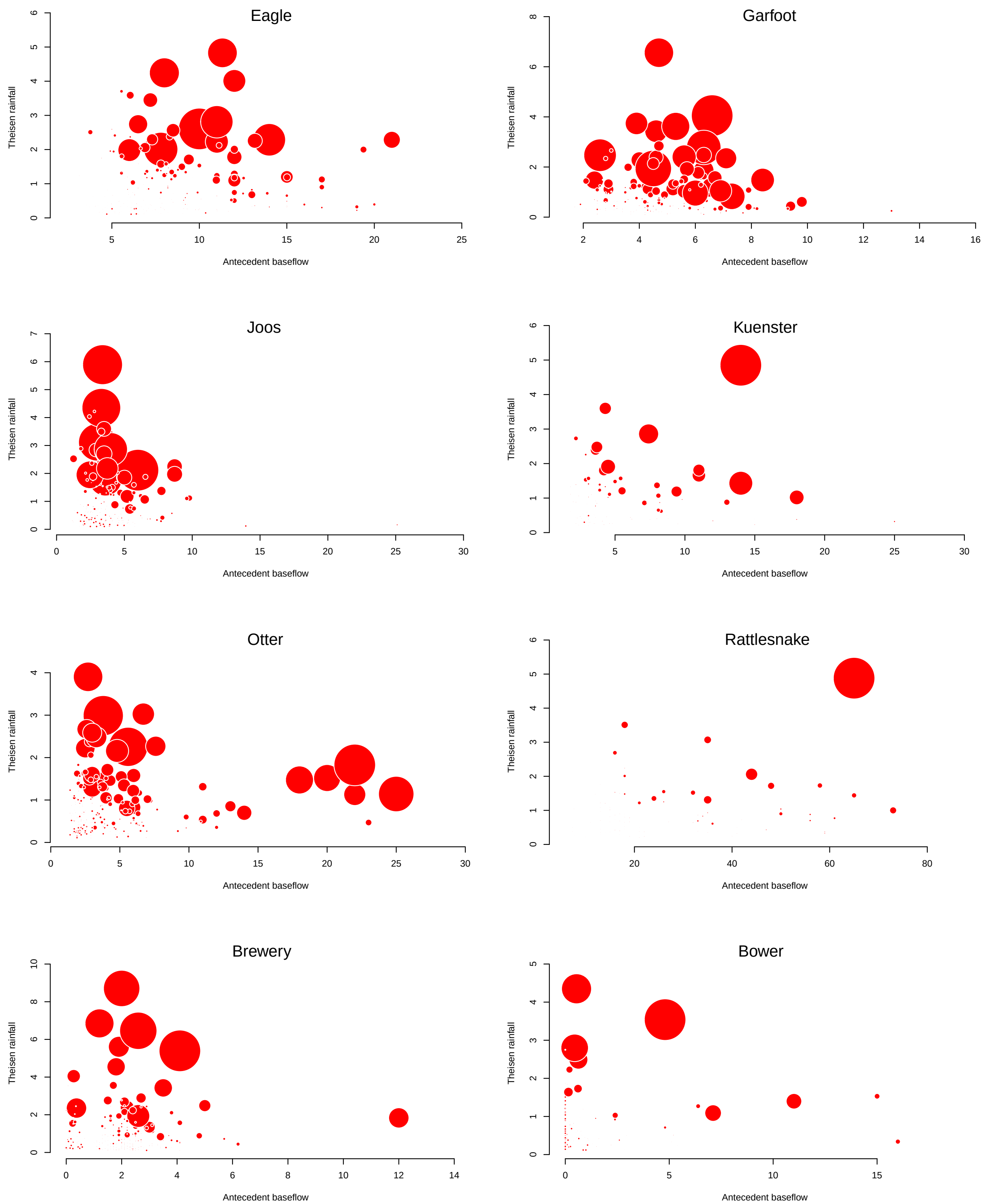

FIGURE 5 – Antecedent base flow is the horizontal axis; theisen rainfall is the vertical axis. Each dot represents one event. The size of the dot shows the total sediment load contributed by that event.