Spatial Variability and the Assessment of Forest Streams

DRAFT SUMMARY

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Summary

Watercourses are a valued part of the Swedish environment. One environmental sub goal concerning watercourses is that no more than 15% of Swedish water courses should be acidified. Initial efforts to assess fulfillment of that goal revealed that Sweden has little chemical or biological data on streams in relation to the number of streams. Most of those streams are also small, and the existing data is heavily biased towards larger watercourses.

Having identified the problem, this study seeks to summarize what is known about spatial variability in the chemistry of streams, with an emphasis on the smaller streams, and suggest how to move towards a more adequate assessment of streams. Two specific approaches were examined. One is the use of monitoring data from small lakes to supplement stream data. The other is the use of synoptic surveys (landscape-scale “snapshots”) to define the spatial variability of headwater streamwater chemistry on catchments smaller than 20 km^2, the effective cutoff for current monitoring of water courses.

The major findings of this project were:

- Small lakes can be useful source of information on stream chemistry at the point in the landscape where a lake exists, provided that procedures are developed to account for spatial and temporal differences between what a lake and stream sample represent.
- Perennial streams generally exist when 1 km of catchment area has accumulated. Monitoring data is collected on streams with catchment areas greater than 20 km^2, mostly on much larger catchment areas. The vast majority of stream length in Sweden has catchment areas 1 - 20 km^2.
- Differences between the chemistry of nearby streams are much greater for headwaters (1-20 km^2 catchment areas) than downstream. Thus we know very little about the distribution of water chemistry and aquatic habitats in headwaters
- Headwaters tend to be more acid and sensitive to acidification than downstream.
- It is not clear about obligations for assessment of headwaters under the Water Framework Directive, but reason to believe headwaters have great ecological significance. Many human actions and management decisions concern headwaters.
- There is a temporal dimension to spatial patterns. Headwaters become more acid at high flow, but many features of the spatial variability are consistent between high and low flow, with DOC an important exception. Persistence of spatial patterns is the basis for predicting high flow conditions from the situation at low flow.
- Map information not currently able to improve the understanding of landscape scale patterns on its own. It is possible that GIS can be used in a stochastic approach where one tries to predict the distribution of headwater chemistry relative to downstream.

Based on these findings, we suggest:

1. Augmenting the national register of watercourses to include streams on the 1:100 000 Blue map
2. Developing routines for using lake chemistry as surrogates for stream chemistry
3. Surveying headwater chemistry in representative basins from across Sweden to create a basis for predicting the variability and systematic offsets in chemistry upstream from where routine monitoring data are collected. Both agricultural and forested catchments should be considered

Background

The first national assessment of the Swedish Environmental Goal ”Only Natural Acidification” came to the conclusion that the data available was not sufficient to make an assessment of the Sub-Goal that no more than 15% of water courses should be acidified. More data is needed, but getting enough data is complicated by the great spatial variability in the chemistry of streams. Much of this variability between watercourses is found in the headwaters, upstream from where the samples have been taken that now exist to assess stream acidification and other parameters. The lower limit in catchment size for monitoring data is about 15 km^2. Far more than half of the stream length is found in catchments with areas less than 15 km^2. Thus there is a large portion of the aquatic ecosystem for which there is little information on.

It is already clear that more data from streams are needed than that which was found in that 1995 and 2000 National Inventories in order to follow up the national environmental goal “Only Natural Acidity” with respect to watercourses, (and perhaps for the requirements of the EU Water Framework Directive). How much more data is required depends on how well one can predict water chemistry variation in a landscape from a limited number of samples. There is also a temporal aspect, since water chemistry varies considerably over time, in response to flow and seasonality.

It is also possible that the variability in map information (forest, wetland, agricultural area, soil type, slope, etc.) is related to variability in water chemistry in a landscape, as well as to how much the average value of a parameter upstream differs from measurements further downstream. Therefore GIS data might be a useful complement to chemical samples to improve assessments of water chemistry at a landscape level. Lakes are another potential source of information, if ways can be found to relate lake chemistry monitoring to streams at the same point in the landscape, since there is more monitoring data for lakes at the smaller end of the catchment size range.

Investigations of the relationship between downstream and upstream chemistry in stream networks could also be used as a basis for empirical estimates of the probability distribution for water chemistry (percentiles and median) upstream from a sampling point. Several comprehensive samplings at the landscape scale have been made, mostly for chemistry, but also some biological parameters. In Våsterbotten, stream networks of ca 50-80 km2 with up to 90 nodes have been samples at Örträsk in 2000 an 2002, as well as in Krycklan from 2002- 2005. At Krycklan, 15 streams have also been followed regularly from 2002 to 2005 to give a picture of the temporal variation. In Southwestern Sweden, the County of Västra Götaland has also made a survey in 2001 of smaller water courses. This project seeks to analyze these data and relevant literature, with an emphasis on the forested landscape, to see if there are patterns that can be exploited in planning an effective monitoring and assessment of watercourses to support environmental goal follow-up and the Water Framework Directive.

Central issues for this report are to:

1. Define streamwater chemistry in a landscape perspective, including how the pattern changes between low flow and high flow, as well as how many streams there are in the landscape.
2. Review the literature of how scale issues have been dealt with in the assessment of streams, including the ecological significance of spatial variability in small streams.
3. What results does one get when applying the existing Environmental Quality Criteria to a landscape where many sample points exist.
4. What can one predict of the distribution of water chemistry, status and human influence from a downstream sampling point, and how that prediction can be improve with GIS and the concept of a representative elemental area (REA)
5. Explore whether stream chemistry can be approximated by lake data.

1. Water Chemistry in the Landscape

Section Summary

The 1:250 000 map shows 144 000 km of watercourses in Sweden. According to the 1:100 000 blue map there are 430 000 km of streams (almost three times more). The 1:50 000 maps show even more kilometres of perennial streams. The red map misses what are first and second order streams on those maps. Over three quarters of the stream length is likely to found in these first and second order streams with catchment areas under 15 km^2, i.e. in a size class where no streams are routinely monitored. Data from a number of different sources was evaluated to estimate the spatial variability of headwater streams, and the relationship to what is observed downstream.

The ca 700 streams from the national inventory in 1995 and 2000 did not give an adequate summary of the situation in the hundreds of thousands of km of Swedish streams. Lakes from the national inventory have been used as stream-surrogates to supplement available data. These lakes, however, were more acid than the streams, raising questions about their representativity. Even with the extra lake data, there remains very little information on the spatial variability of water chemistry at a catchment scale of less than 15 km2, despite the fact that perennial streams appearing before a single km^2 of catchment area has accumulated upstream from a point.

Four 50-80 km2 catchments in Västerbotten are among the few places where that headwater variability has been quantified. Essentially all nodes in the stream networks of these four catchments (40-90 points) were sampled on several occasions. There was greater inter-stream variability in headwater chemistry than downstream. The headwaters were also more acid than what was sampled downstream at catchment sizes over 15 km2. Downstream, the EQC assessment of acidification showed little human influence, but upstream the full range of human influence was indicated. The

At high flows, the variability in headwater chemistry persists. DOC is an exception, though, in that its inter-stream variability decreases at high flow. Most parameters dilute at high flow, reducing the absolute range of variability, but retaining the relative degree of variation. That consistency in the inter-stream variation patterns between base flow and high flow is an important basis for modelling the situation at peak flow from observations at base flow (the one-point approach).

Västra Götaland sampled randomly from all its streams on the 1:250 000 scale map (Red map). When compared to the national inventory data in their region, their data set had more smaller streams, and the smaller streams were both more acid and more sensitive to acidification. This is similar to what was seen in Västerbotten

Table 1. Summary of data used in this report

Source/Site	Number	Hydrology	Comment/Size
National Inventory 95 and 00			Nation-wide, random
Streams	699	Mixed flow	median 48 km^2
Lakes	2716	Mixed flow	median 3.6 km^2
Ottervattsbäcken 2000	61	Low flow	Västerbotten 0.2-78 km^2
Ottervattsbäcken 2002	66	Low flow	Västerbotten 0.4-78 km^2
Sörbäcken 2000	41	Low flow	Västerbotten 0.2-60 km^2
Krycklan 2004	86	High flow	Västerbotten 0.2-58 km^2
Krycklan 15 2003-2004	15 x 40	Time Series	Västerbotten 0.2-68 km2
Västra Götaland, 1999	220	Low Flow	SW Sweden

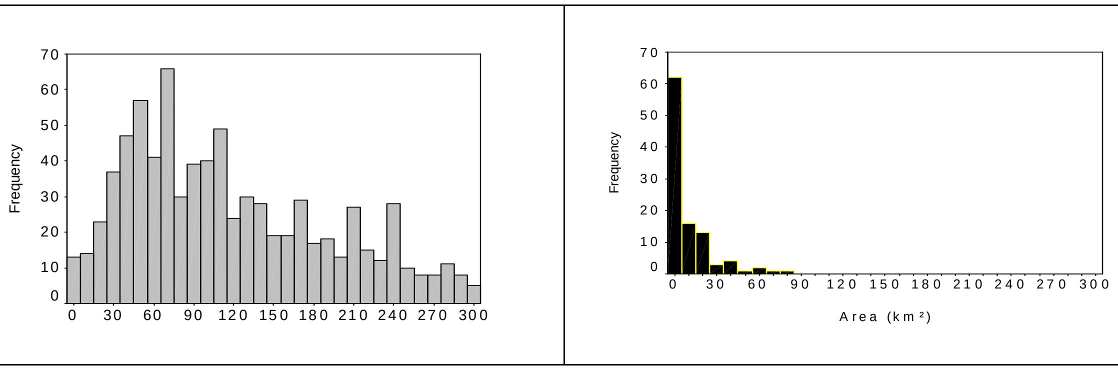


Figure __1. Left pane: distribution of the catchment size (km^2) for watercourses in the Swedish monitoring programs (National and SRK), showing only watercourses < 300 km^2 (median is 277 km^2, n = 1339). Right pane: catchments sizes from the two study catchments in this thesis (n = 103).

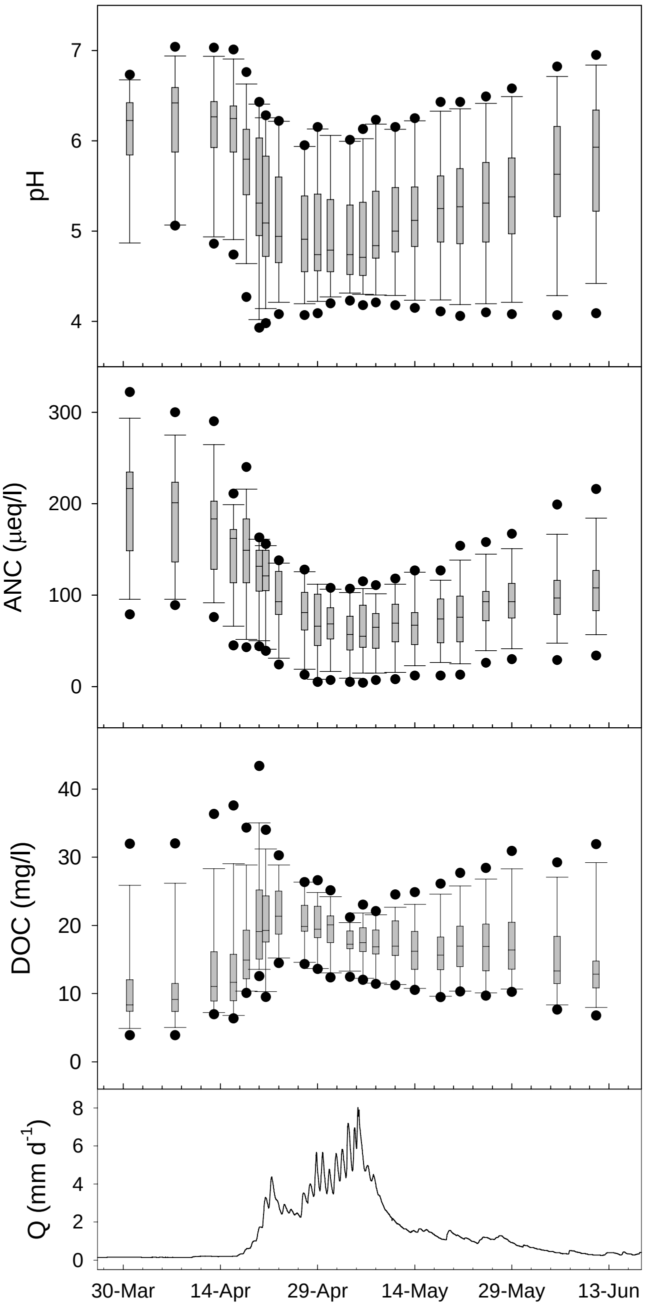


Figure 2: Box-and-whisker plots of variability within 15 intensively sampled sites in the Krycklan catchment over the course of spring flood 2004. Center line is median value, box is bounded by 25th and 75th percentiles, whiskers define 10th and 90th percentiles, outliers depicted as dots. Panel A: pH, Panel B: ANC, Panel C: DOC, Panel D: Discharge at a representative site.

2. Approaches to Scale in the Literature

Catchments are clearly delineated natural systems that display a complex multi-scale dynamics and where numerous processes are operating at the same time. That spatial variability in water quality changes with catchment size (Temnerud and Bishop, 2005) and during episodes (Nagorski et al. 2003; Buffam et al. 2004) is well established. However, the effect of catchment size and the influence of landscape characteristics on runoff and water quality are currently poorly understood (Gergel et al, 1999; McGlynn et al. 2004). Designing management and decision tools that operate at different spatial and temporal scales dedicated to water resources is therefore a challenging task. Those tools must not only include scale dependent aspects but also bridge the gap between scale dependency, temporal changes and variability caused by different landscape elements.

Management and the Scale Issue in Europe:

Within the European Union the scale issue has gained a great deal of interest lately because of its implications in water management. This recent interest has been driven by the newly implemented Water Framework Directive, which has changed the management focus from politically defined borders to catchment boundaries. In this new directive water is not only seen as a resource serving functional purposes (e.g. as water for agriculture, industry and domestic users), but also as a major amenity for recreation, health, ecology and aesthetic values. These new principles that include both economic and social aspects will require a new integrative approach in water management that consider both variability and scale as well as a better understanding of landscape influence on hydrology, fluxes of solutes and transport of contaminants.

The WFD specifies that all water is to be monitored and classified. No explicit lower boundary is specified. But the typology of streams being developed by the EU starts with catchment sizes of 10 km2. This may be where reporting obligations begin for the WFD, but not necessarily where management interest stops in Sweden. Much of the human impact and management decisions concern catchments with areas less than 10 km2. Unfortunately, there is not much in the way of ecological studies in small headwaters to substantiate the biological importance of those headwaters. But on the other hand, no “lower bound” of catchment size has been identified by the studies the have looked at the importance of scale.

Up scaling – The Scientific Problem

The question of how different scales interact and how we can translate processes and understanding at one scale to interpret patterns and results at another scale is fundamental in water management. A basis when dealing with these scale issues is the transformation of mechanistic understanding and/or empirical observation at a certain scale for use at another scale of interest. Up-scaling involve information transformation from smaller scales to understand patterns and predict effects at a larger spatial scale. Conversely, down-scaling deals with disintegration of information from a larger scale to understand processes and variability at smaller scales. When dealing with water quality scaling is often associated with large uncertainty because of nonlinear relationships in hydrological and biogeochemical processes (Saracino et al. 2004). And there is currently a debate about scaling within the hydrological and biogeochemical community and the pros and cons of physically based approaches, simply lumped models, neural network models and uncertainty analyses. The bottom line is that scaling is an integral part of water management but that it must be handled with care in order to avoid misinterpretation of patterns and over-emphasizing the importance of discrete processes.

Most questions about sustainability of water resources and protection of aquatic ecosystems come at the landscape scale. The best answers we have about the relevant processes, however, are found at the scale of plots, hillslopes and small catchments. Most scale dependent issues in environmental management therefore entail up-scaling of small scale studies to assess patterns and solute variability in larger basins. A common pattern is that as the size of the catchment increases, both the spatial and temporal variability in water and solute fluxes found at the local scale becomes more attenuated. Many challenges however remain unsolved when trying to quantify the importance of scale for predicting impact on aquatic ecosystems. Although most focus on scales in the biogeochemical and hydrological literature have been on the nutrients (Strayer et al. 2003) and sediment issues (Schreier and Brown. 2004) examples from both DOC (Clark et al, 2004) and acidification related work (Reynolds et al. 2001) as well as from stream biodiversity (Johnson et al. 2004) have recently been presented. Important questions when dealing with scale in water management are: What is the nature of variability? How can we conduct sampling to minimize bias? Can the changes observed at different catchment sizes be associated with causal factors and hence be predicted? And what are the implications for water management and environmental assessments?

Assessment of diffuse non-point source of nutrients is one area that has generated a large interest in the literature the last decades. Many elements may have no or only limited impact locally, but will become important because of cumulative effects downstream. Studies of nutrient export include watersheds ranging from a few hectares to large rivers with basins covering over 1,000,000 km2. Large-scale investigations are often based on simple empirical models and correlations to predict nutrient export (Jordan and Weller, 1996; Caraco et al, 2003). Promising results using a simple approach have been presented by Caraco and Cole (1999) that could explain over 80% of the variation in nitrogen when including population density and anthropogenic load. Contrary to large-scale studies, investigations in small catchments often focus on mechanistic process-understanding of the complex interactions at plot-scale or at discrete hillslopes (Mitchell et al. 1999; Kram et al. 1999). These complex approaches often make the models difficult to apply to other sites without extensive calibration and validation efforts. This is especially troublesome in water resource management where lack of calibration data and scientific expertise often impede such attempts.

Promising efforts have been made to overcome the gap between process-based mechanistic models and correlative approaches in order to improve the operational models that can be used for water resource management purposes. One important contribution has been the understanding of how the riparian (near stream) zone controls temporal and spatial variability. This understanding results from research in temporal and boreal regions (McGlynn and McDonnell, 2003; Bishop et al. 2004), working on a range of issues from eutrophication to mercury and carbon budgets. The importance of the riparian zone is also recognized in Sweden, where a better understanding was identified as the key challenge for catchment science in Sweden at a recent workshop (Löfgren, 2003). Another remaining question is how the importance of riparian soil changes as one moves from first order streams to larger rivers.

One approach that recently has been used in Canada for nutrient and sediment dynamics is mass-balance budget estimates linked to detailed GIS-based land use information (Schreier and Brown, 2004). Similar model frameworks has been developed by Caraco et al. (2003) and Edwards et al. (2000) to predict variability in NO3, by Findlay et al. (2001) and Creed et al (2003) for variability in DOC and by Johnson et al. (2000) and Kling et al (2000) for mineral element fluxes. The general basis for most of these studies is that they use dominant landscape elements for predicting scale effects on runoff and solute transport. In Sweden one promising approach has been developed by McGlynn and Seibert (2003) who use a hydrological landscape analysis (HLA) technique that enables upscaling of process-based investigations to a landscape level. This method has been shown promising in relation to variation in runoff but much work remains before it can be used for predicting spatial and temporal patterns in water quality.

Most of this work on predicting features of water quality does not seem to have reached outside the scientific community to be implemented into the different national water management authorities. One departure from this pattern is the River Environment Classification (REC) that has been developed and used in New Zealand (Snelder and Biggs, 2002; Larned et al. 2004). The REC is a system that can be used to classify and map spatial patterns in river ecosystems. It is based on a physical understanding of fluvial processes that can be used to discriminate patterns of in-stream processes and spatial pattern in water quality based on hydrological variable, temperature, geomorphology, physical habitats and water chemistry. The REC function at a range of scales and allows for integration of both local scale processes and landscape patterns (Snelder and Biggs. 2002).

Integrated River Basin Management (IRBM) is another approach that is not only used within the research community. IRBM is a multidisciplinary and multi-scale approach for water management that deals with technical, as well as socio-economic and ecological aspects. This approach calls for an integrated watershed approach and involves a comprehensive set of analysis steps, supported by mathematical tools for the analysis of natural resource systems in a socio-economic context (Schultz 2000). The purpose of IRBM is to structure the decision-making processes and provide water management alternatives for complex management questions. IRBM is mostly used in larger rivers at a national level and directed toward socio-economic and political questions (Quinn et al. 2004). But IRBM is also used to assess the ecological statues of catchments and water bodies and to estimate the effects of nutrient loading as well as suggest methods of reducing nutrients. However in this context the need for integration of more physically based techniques including both hydrological and biogeochemical modeling frameworks would be useful (Quinn et al. 2004).

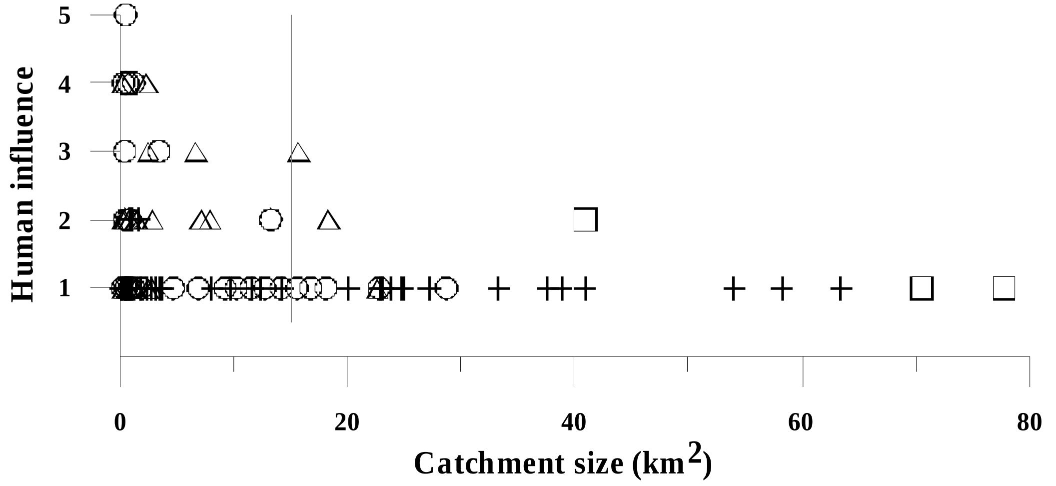
Downscaling – Sweden's Management Problem

Contrary to the methods and approaches discussed above acidification assessments of small streams in Sweden often deal with down-scaling. This implies that we from a downstream sampling location need to predict the acidity/acidification status in upstream smaller streams. Compared to up-scaling the issue of down-scaling has received much less attention in the scientific literature. In the case of down-scaling we move from integrated information in larger streams to ask specific questions about the variability in chemistry and runoff in the contributing sources. Because acidity in a downstream location not solely dependent on the smaller streams above the sampling location but also of in-stream processing and ground water input, the question becomes even more complex. It could be argued that similar modeling frameworks that are used in up-scaling could be used for down-scaling. However in order to improve the predictability of small scale variability in water quality a better process understanding than is currently available will be required, as well as appropriate empirical data. And much work still remains before we can combine our understanding of ecosystem functioning at different scales in order to predict and restore anthropogenically induced changes on aquatic ecosystems.

3. Application of EQC in the Landscape

Section Summary

The EQC were applied to the chemistry data from the synoptic surveys from Ottervattsbäcken, Sörbäcken and Krycklan. The downstream sites had less acidity and a lower degree of human influence. The upstream sites had the full range of status and human influence. This is consistent with the difference in stream chemistry median and variability observed in these catchments. In Västra Götaland, this pattern is an indication that acidified sites are missed. In Västerbotten's inland, it should be seen as an open question as to whether the headwater sites really have experience such a wide range of human influence. The acid deposition in these areas has been small, and there is no apparent difference in the sensitivity of these catchments to acidification (weathering rate of soils or depth of soils). So it may well be that these headwater sites are subject to "false positives" from the EQC.



Classification of human influence with regards to acidification, based on alkalinity, according to SEPA EQC . Data from Ottervattsbäcken in Västerbotten's inland, O (□), with branches O1 (○) and O2 (△), and Sörbäcken, S (+) year 2000, n = 98, sampled during low flow.
The 15 km^2 minimum size of watercourse catchments in Sweden's national inventory of stream chemistry year 2000 is denoted by the vertical grey line.

4. Predicting Upstream Chemistry from Downstream Chemistry

Section Summary

The problem of assessing streams would be simplified if the chemistry of the downstream site held some indication of the range and mean of the chemistry at upstream sites. While it seems difficult to believe that the downstream chemistry alone contains such information, an attempt was made to model the upstream mean and range in acidity status from the chemistry observed at the downstream site using the multivariate PLS method. These did not succeed. An alternative was to use map information to predict the upstream mean and range of variation.

5. Lake Chemistry as Complements to Downstream Monitoring

Section Summary:

Lakes can be used as a surrogate for streams. Difference between National inventory lakes and streams are related to several factors. First lakes are a reservoir. Periods of high flow with more acidity will give a lake a more acidity than a stream sampled during a period of low flow with higher pH in some regions. Lakes are also not a statistically representative sample of streams. To use lakes as surrogates, the issue of how to upscale from lake samples to streams needs to be addressed. Lake density a factor for how well lakes represent streams

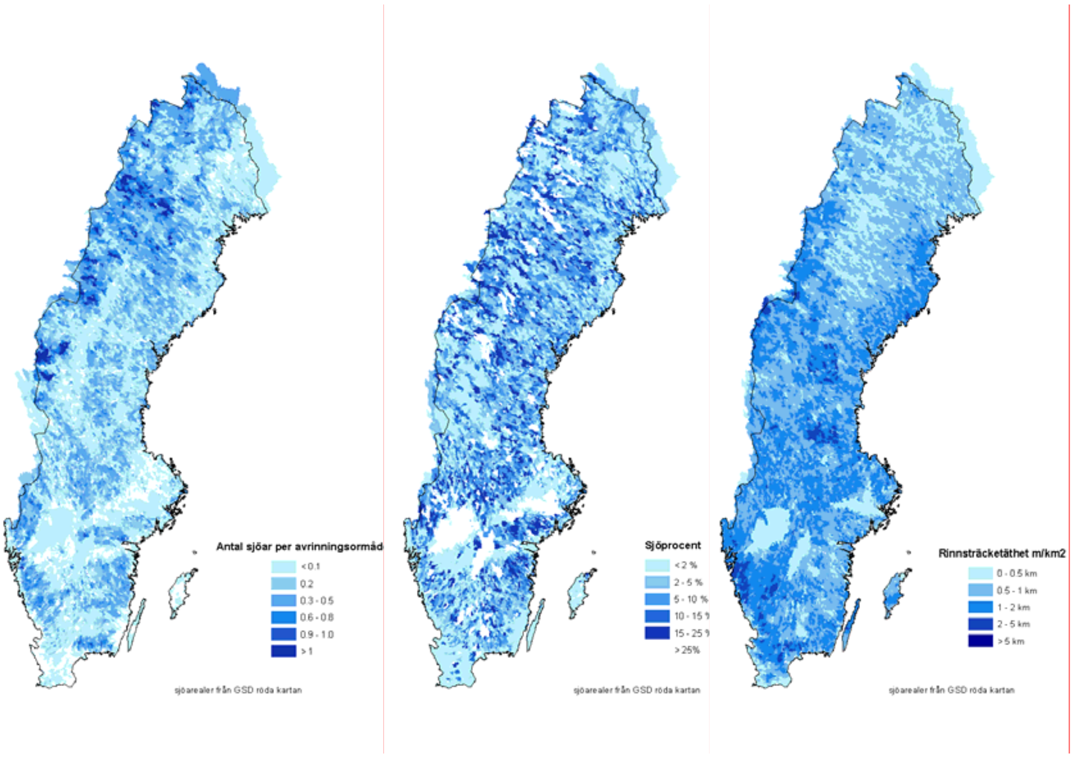


Figure 5. Lake number density, Lake percentage and stream density.

6. Discussion

Streams are the capillary network that embeds freshwater ecosystems in the landscape. Assessment of the stream network presents special challenges, as is illustrated by this study.
The sampling of all stream confluences in several catchments revealed that the headwaters were highly variable. In fact, the range of DOC, absorbance, pH and alkalinity found in the headwaters was almost as great as seen in the entire forested area of northern Sweden by the national survey of watercourses conducted in 2000. Furthermore, the entire range of Current Status classes for DOC, pH and alkalinity and Human Influence classes of acidification were found in the headwaters of the catchments (Figure XX).

Awareness of spatial variability is not new. Already in the first decades of the 20th century, the special character of headwaters had been noted in Sweden (*19*). Nonetheless, how to deal with this variability in monitoring and assessment has yet to be addressed.

In Sweden there are roughly 144 000 km of streams as measured on the national 1:250,000 maps. The length is 430 000 km if the 1:100 000 map is used. The national survey measures some 800 points on this network, but only a few with an upstream catchment area smaller than 15 km^2 The majority of the length of perennial streams is found in catchments with areas under 15 km2 (*40*). A large part of all streams length is thus overlooked in the national survey. In this study the headwaters, stream order 1, made up approximately 40% of the total catchment area and three quarters of the stream length. The relationship between stream order, using 1:50,000 maps, and catchment size (see Figure 2) indicates that the Swedish National Survey in 2000 mostly sampled streams which had a stream order 3 or greater.

The current Swedish monitoring strategy with 15 km^2 as the lower limit in catchment size gives a relatively “representative” picture of the landscape, in that much of the variability upstream is hidden. This is consistent with a sampling strategy based on the idea of an REA where small-scale variability is often considered as “noise” to be suppressed (*15*). Even if much of the aquatic features and species valued by society are found downstream from the 15 km^2 boundary for sampling, the headwater environment influences the downstream ecosystem (*17*), and provides much of the water and dissolved constituents. The water chemistry experienced by the biota in the headwaters is much more variable than downstream. In this study we have only focused on the water chemistry, but in other boreal streams, the number and type of species is likely to differ between headwaters and downstream (*16*). The headwaters could have species that do not occur downstream.

The European Union’s Water Framework Directive will mandate assessments of all waters, with no lower limit in catchment area currently specified. Some effective lower catchment limit appears likely to mean that headwaters with catchments under 10km2 do not have to be reported. Nonetheless, knowledge of how the headwaters relate to what is observed downstream will be essential in devising strategies for assessing the multitude of headwaters. Strategies for assessing water chemistry in landscapes would benefit from knowledge of consistent patterns in the relationship between headwaters and downstream. Acidification, as assessed by EQC, is generally higher in headwaters, as is DOC. These differences result from several factors including: the frequency of mires along headwaters, lakes, in-stream/hyporheic biological geochemical processes, and the effect of inflowing groundwater downstream. The degree of difference from headwater to outlet, however, varied between the 4 catchments in this study from Västerbotten.

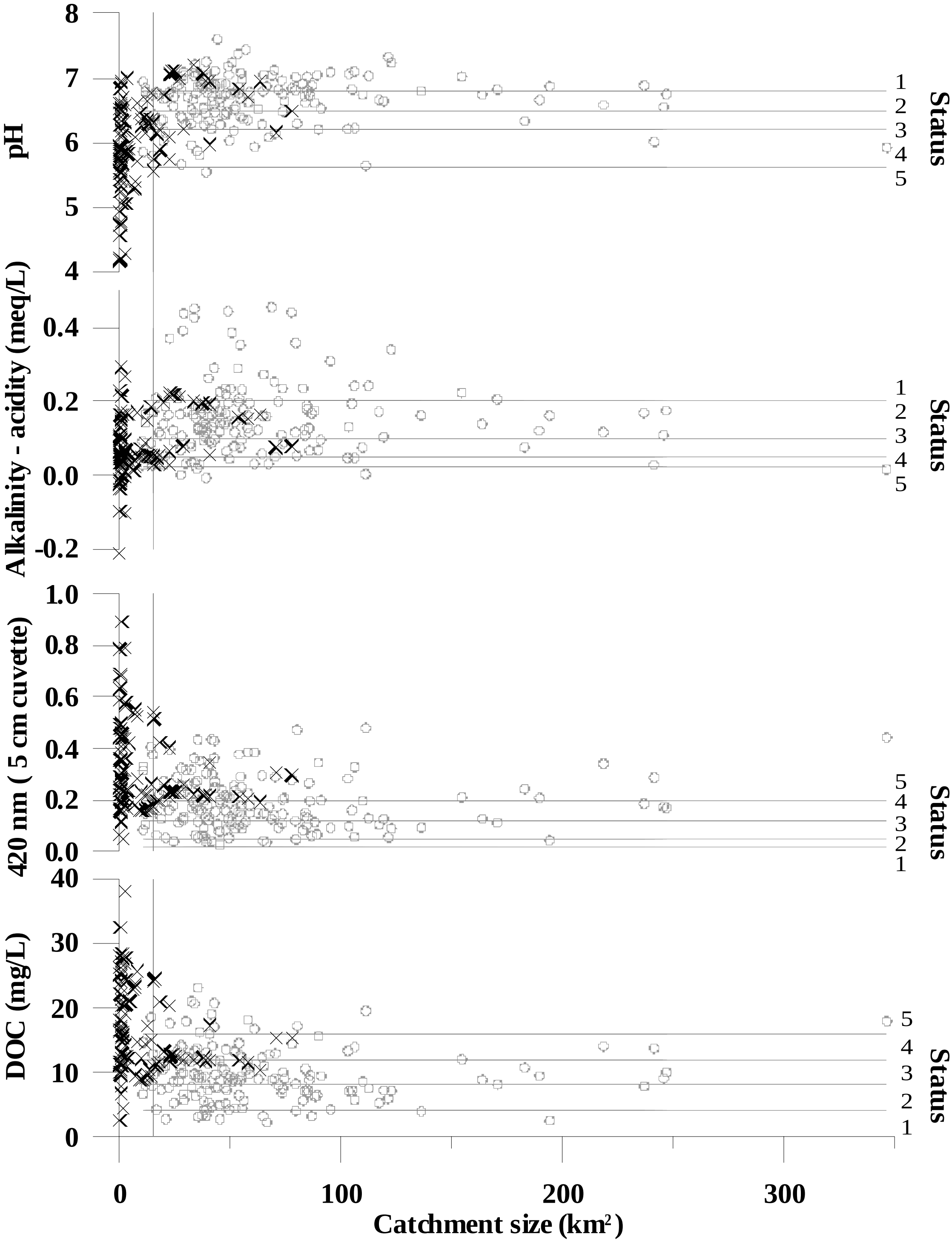


Figure 2. A comparison of water quality in this study (black crosses, year 2000, number = 103) and Sweden's national inventory of stream chemistry year 2000 (grey circles, number = 163). The vertical grey line at 15 km^2 represents the minimum catchment size in the national inventory. The points plotted from the national inventory were from Sweden's northern counties using all samples collected below tree line, with arable and urban land under 1%, and catchment size < 350 km^2. Horizontal grey lines are the SEPA EQC (*11*) status class boundaries, see

One strategy for addressing the challenge of spatial variability would be to find map parameters that correlated to water chemistry. This would facilitate predictions of the variability across the landscape in water chemistry from the variation in map parameters. As has been found for other studies correlations were indeed found between one of the key water chemistry parameters for this site (DOC) and map parameters. It was not possible, though, to take a model of water chemistry based on map parameters and apply it with good results on nearby basisn.

A further complication in the interpretation of spatial surveys is that water chemistry varies with time, generally correlating to variation in discharge.

Similarities found in spatial patterns between low flow and high flow gave reason to believe that assessment based on low flow can be relevant to high flow conditions if appropriate transfer functions can be found, similar to those used in the episode model of how ANC at low flow relates to that at high flow.

Conclusions

In the forest landscape of Sweden, sampling at a scale of Stream Order 3 (or excluding catchments smaller than 15 km^2) may be adequate if generalized values are desired. The situation in the headwaters, however, would not be characterized. This is a serious omission because such a large part of the stream length is found in these small streams. This study highlights the importance of accounting for spatial variability in assessments of running waters, even in relatively pristine areas. The nature of drainage networks with many headwaters and progressively fewer downstream watercourses complicates the monitoring of headwaters. This, however, is a challenge that must be confronted for both national assessment, and possibly obligations under the EU Water Framework Directive. In this study, some patterns were observed, but much more such data is required to devise regional sampling strategies, and the ways to use GIS data to support those strategies.

- Small lakes can be a useful source of information on stream chemistry at the point in the landscape where a lake exists, provided that two factors can be accounted for. One is that a lake water sample integrates stream chemistry over a period of time. The other is that the distribution of lakes in a landscape can differ from that of streams.

- Perennial streams generally exist when 1 km of catchment area has accumulated. (Drainage may contribute to interruptions in flow during drought.) Monitoring data is collected on streams with catchment areas greater than 20 km^2, mostly on much larger catchment areas. The vast majority of stream length in Sweden has catchment areas 1 - 20 km^2 (i.e. where monitoring is not conducted.).

- Differences between the chemistry of nearby streams are much greater for headwaters (1-20 km^2 catchment areas) than downstream. Thus we know very little about the distribution of water chemistry and aquatic habitats in headwaters.

- Headwaters tend to be more acid and sensitive to acidification than downstream.

- It is not clear about obligations for assessment of headwaters under the Water Framework Directive, but there is reason to believe headwaters have great ecological significance. Many human actions and management decisions concern headwaters.

- There is a temporal dimension to spatial patterns. Headwaters become more acid at high flow, but many features of the spatial variability are consistent between high and low flow, with DOC an important exception. Persistence of spatial patterns is the basis for predicting high flow conditions from the situation at low flow.

- Map information is not currently able to improve the understanding of landscape scale patterns on its own. Possible that GIS can be used in a stochastic approach where one tries to predict the distribution of headwater chemistry relative to downstream.

Based on these findings, we suggest:

  - Augment the national register of watercourses to include streams on 1:100000 Blue map

  - Develop routines for using lake chemistry as surrogates for stream chemistry

  - Survey headwater chemistry in representative basins from across Sweden. This will create a basis for predicting the variability and systematic offsets in chemistry upstream from where monitoring data is collected.

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