INVITED COMMENTARY
HP TODAY
HYDROLOGICAL PROCESSES
*Hydrol. Process.* **22**, 1239–1242 (2008)
Published online 11 March 2008 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.7049

# *Aqua Incognita*: the unknown headwaters

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*Received 4 March 2008*
*Accepted 5 March 2008*

**Running water comprises just over one millionth of the world's water. The importance of those streams and rivers as a resource for human welfare and biodiversity, however, is far out of proportion to that minuscule fraction. This explains why protecting running waters (the flow regimes, water quality and biota) is such a vital concern for society. Yet for all the focus and concern, how much do we actually know about these running waters, and the lotic habitat they comprise?**

**Consider what would happen if one asked any national environmental authority to assess the basic chemical and ecological status of running waters. At the river mouths, there would be enough information to make a reasonable assessment of the status. But somewhere on the way upstream, available data would run dry, long before most stream channels did (in non-arid regions).**

**In Sweden, with an ambitious programme for monitoring and assessing surface waters, it came as a surprise several years ago to realize that the length of all perennial streams on the country's maps was not known. When that was modelled in the form of a 'virtual network' from a 50 m $\times$ 50 m digital elevation model, the total length turned out to be 530 000 km (*ca* 1 km/km$^2$), which was double the previous estimates. The length was independently confirmed by another group using remote sensing data (Esseen *et al.*, 2004). Further analysis of the virtual network revealed that over 90% of the stream length had catchment areas under 15 km$^2$. Although this might seem merely of academic interest, 15 km$^2$ is the lower limit for what has been surveyed on a national scale in Sweden. Does this mean that we have missed something important in our assessment of water resources?**

**When the chemistry of all flowing headwaters in a single 78 km$^2$ catchment was compared to the 2000 Swedish national survey of running waters, there was as much variability within the headwaters of that forested catchment as could be found in a statistically representative sample of over 260 000 km$^2$ of Sweden's boreal forest waters (Temnerud and Bishop, 2005). Other studies on biota have not just found such headwaters to be teeming with biodiversity, but also found species that are endemic to headwaters (Meyer *et al.*, 2007). Discrete inquiries were made to see if national agencies in other countries of North America and Europe had come further in the documentation and assessment of headwaters. The answer was 'no'. There are, however, some significant efforts (e.g. Hutchins *et al.*, 1999; Smart *et al.*, 2001; Likens and Buso, 2006). The most notable is the US Environmental Protection Agency's (EPA's) 'Wadeable Stream Assessment (2006). But since many first and second order streams are not on the US maps, and the assessment went up to fifth order streams, headwaters are likely to be seriously underrepresented even in that landmark survey.**

**In most regions, the overwhelming majority of stream length lies beyond the frontiers of any systematic documentation and would have to be represented as a blank space on the assessment map. This means that for the majority of streams that support aquatic life, a systematic understanding is lacking on water quality, habitat, biota, specific discharge, or even how many kilometres of such streams are there. This blank space is so vast that it deserves a name to help us at least to remember that it is there. We propose calling it '*Aqua Incognita*'.**

*Aqua Incognita*'s realm is comprised largely of the capillary network of small streams where running water begins its journey downstream to merge with other streams that contribute to rivers and lakes. We believe that these headwaters are there, but we do not know where they are, or for that matter really what they are, other than for a few small catchment outposts in the form of research sites and some pioneering synoptic surveys.

How have headwaters retained their anonymity despite being so nearby to everywhere? One reason may be that we know so much about a few headwaters. Hubbard Brook, Turkey Lakes, Storgama, Panola, Krycklan/Svartberget, Lysina, Bear Brook, Sleepers River, Auerbach, Gårdsjön and Maimai, are a few showcases of how much one can learn about headwater streams. But that is different than being able to say how this knowledge represents headwaters within a region, and how they are changing under the influence of land use, atmospheric deposition and climate change. Perhaps the steady flow of new questions generated from the detailed studies has distracted us from the task of generalizing. Intensive studies on selected sites are a necessary complement to, but never a substitute for, systematic inventories and classification systems needed to make an assessment of headwaters and how they are altered by human influence.

Another factor that has kept us from achieving a more systematic understanding of headwaters is the sheer magnitude of the problem. Sweden's headwaters alone stretch more than ten times around the earth's equator. If it seems hard to grasp how that distance can be packed into a landscape, that seemed pretty well-filled with forest, farms and towns, then consider that this length is also that of the blood vessels in three adults. Such is the nature of branching networks.

Others, largely in North America, have been calling attention to the importance of headwaters (e.g. Lowe and Likens, 2005). In Europe, the aquatic assessment community has been so focussed on the EU Water Framework Directive that perhaps there is little energy left over to expend on moving the boundary of reporting to include a host of undocumented waters. But, in the USA protection of headwaters under the Clean Water Act has been challenged by policies of the current administration and a Supreme Court decision. This has focussed attention on the need to define the value of headwaters (*cf* the special issue of the Journal of the American Water Resources Association devoted to hydrological connectivity between headwater streams and downstream waters, summarized by Nadeau and Rains, 2007).

It is, however, a long way from recognizing the problem of unassessed streams to solving it. If future expeditions are going to explore and thus reduce the extent of *Aqua Incognita*'s realm, there are two questions that need to be addressed:

1. Are the headwaters important?
2. Is it possible to make a meaningful assessment of something so vast and changeable?

The tremendous importance of the ecosystem services provided by headwaters seems self-evident. Headwaters are where waters meet the land, and those headwaters are instrumental in conditioning the natural and unnatural inputs from the landscape into forms that downstream ecosystems and human systems are adapted to utilize. Whether it is dampening floodwaters (Sanford *et al.*, 2007), cycling nutrients (Bernhardt *et al.*, 2003), or buffering the impact of pollutants (Klaminder *et al.*, 2006), the services provided by headwaters are invaluable. And for the biota, there is the sheer extent of the headwater habitat, with its great diversity, linked by a flowing network of water that serves as a conduit for migration and refuge.

The processes and habitats in these headwaters are as sensitive if not more so than downstream waters to disturbance, including climate change (Baxter *et al.*, 1999; Buttle and Metcalfe, 2000). The scale of headwaters are also the scale at which many local management decisions occur, from how to protect the riparian zone in a forest harvest or a farm field, to locating a parking lot or converting forest land to housing. This means that information on headwaters could make a tangible difference in operational water management. At a more extensive scale, any regional management policy is a prescription for headwater management, whether or not the implications for lotic habitat and the quality or flow regimes of headwaters are explicitly recognized.

Even if one were determined to fill in the blank space of *Aqua Incognita*, there is the second issue of how a meaningful assessment can be done—if it is possible at all. Not only is there great variability in space, but every stream also has a temporal dimension which is changing hour by hour and day by day with changing flow rates and season. The spatial and temporal dimensions of individual headwaters are also linked in networks that have myriad possible permutations and combinations with significance for the aquatic biota navigating these networks. So, the task of defining *Aqua Incognita* is not to be underestimated. However, science is full of success stories, once an issue is recognized. A number of efforts have been made to give headwaters their due, some going back almost a century (Eriksson, 1929)

We see potential in combining monitoring information from downstream sites with map data on headwater catchments to aid in assessment of headwaters. In Fenno-Scandia and some other parts of the boreal zone, this can include data on small headwater lakes (catchment area *ca* 0·5–5 $km^2$) that can be used as a surrogate for streams (e.g. Laudon and Bishop, 2002). An example of such downstream data is the 1995 Nordic survey that sampled lakes down to 4 ha from Ireland to the Kola Peninsula (Henriksen *et al.*,



DOI: 10.1002/hyp

1998). Using such data, we can try to relate what exists upstream in a stochastic manner to what is observed downstream.

A demonstration of this concept has been made in Sweden where a systematic survey of information on the chemistry of *ca* 750 streams with catchments over 10 $km^2$ was collected in both 1995 and 2000 in a regionally stratified random sample (Johnson *et al*., 2004). To make an initial characterization of the 90% of channel length upstream from the sample points, we had data on the chemistry of headwaters from half a dozen synoptic surveys. On each of these, nearly all the tributaries within 60–100 $km^2$ catchments were sampled in the course of a few days (e.g. Buffam, 2007; Temnerud *et al*., 2007). Using pH as an example, systematic patterns were found in the mean of headwater pH as a function of downstream pH (Figure 1(a)), as well as the standard deviation of pH among streams as a function of catchment area (data not shown). The skewness of the pH distribution in headwaters was also found to change systematically, with more acid median pH being associated with headwaters skewed to the low pH end of the range, while higher pH downstream had headwater pH distributions skewed to the higher end of the pH range (Figure 1(b)). With that information, an initial estimate of the pH in streams with catchment size classes from 2 to 25 $km^2$ was made (Figure 2).

The purpose of this demonstration is simply to present an approach which might encourage (or possibly provoke) others to find ways to push back the frontiers of *Aqua Incognita*. We believe it suggests that data on downstream sites can be exploited to develop a stochastic description of headwaters. This approach may be complemented by the use of map information. While maps alone have generally not been able to accurately predict water quality and biota on their own (Reggiani and Schellekens, 2003), they may help add structure to constrain stochastic predictions of headwater conditions from downstream observations.

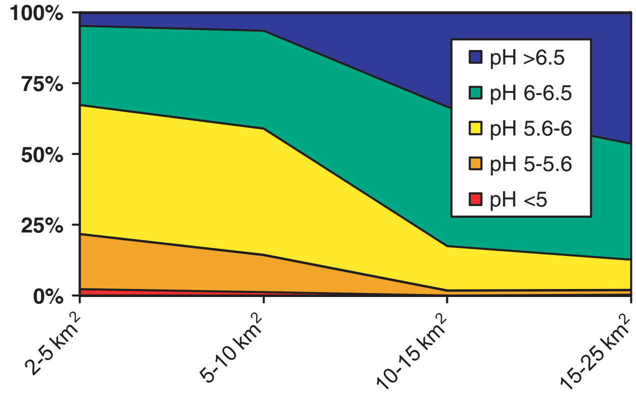


**Figure 2. The estimated distribution of pH in streams as a function of size. The estimate for catchments larger than 15 $km^2$ is based statistically on representative observations from the 1995 Swedish national stream survey (Henriksen *et al*., 1998). The distribution for smaller catchments is based on the relationship between downstream pH and the mean of upstream headwaters (Figure 1(a)), as well as the standard deviation and skewness of headwaters (Figure 1(b)) from available data on stream networks in Sweden**

The unknown has always beckoned explorers. Others can make a case for going to Pluto and beyond. We believe it is high time that catchment science embarked on a new age of exploration to the unknown headwaters lurking in the landscape we know so much else about. Exploring *Aqua Incognita* will reveal the patterns of interaction between life and landscape in the upper reaches of river basins. Understanding these patterns will improve society's ability to effectively steward water resources and aquatic biodiversity, benefiting all who depend so much on the headwaters we know so little about.

In a few years the International Association of Hydrological Sciences (IAHS) decade for 'Predictions in Ungauged Basins' will draw to a close. When that happens, perhaps we should turn our focus to a new initiative: exploring headwaters—the realm of *Aqua Incognita*.

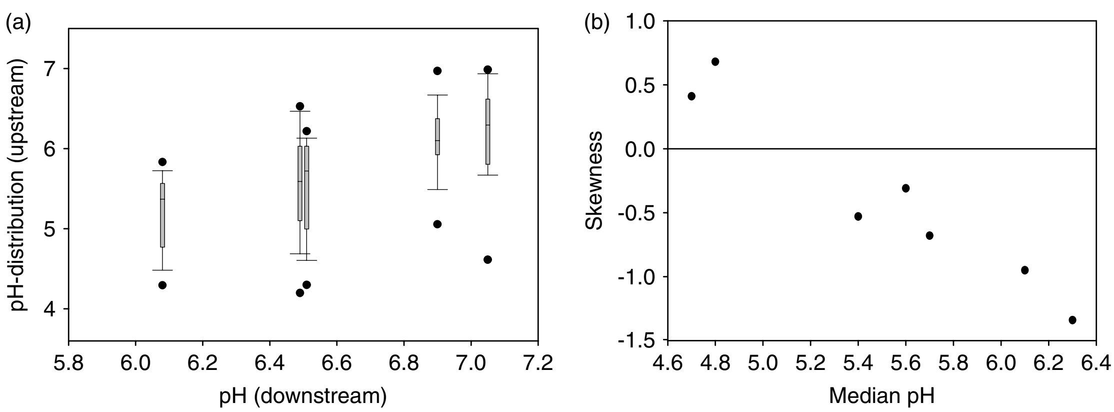


**Figure 1. Each distribution represents a discrete sampling occasion. The catchments are a mixture of boreal forest and wetlands in Sweden. (a) The distribution of pH in headwaters (catchment area 0·5–5 $km^2$) upstream from the observed pH in fourth order streams (catchment area 50–80 $km^2$). (b) The skewness of the pH distribution in the headwaters of different stream networks as a function of the median pH in these headwaters (catchment area 0·5–5 $km^2$)**




DOI: 10.1002/hyp

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