30th March 2015

In response to comments and reviews in the interactive discussion of our manuscript "Dye tracing for investigating flow and transport properties of hydrocarbon-polluted Rabots glaciär, Kebnekaise, Sweden", we thank two anonymous referees for their feedback, our response to which can be found below, and Mauri Pelto for comments received following the end of the interactive discussion period, which have been addressed in the revised manuscript. We herein submit our response (*in italics*) to each of the reviewers original comments (normal text), followed by a revised version of the manuscript with changes identified throughout the text.

Kind regards,

Caroline Clason, Caroline Coch, Jerker Jarsjö, Keith Brugger, Peter Jansson and Gunhild Rosqvist.

Response to anonymous referee 1:

<u>Specific Comments</u>

In general, I think the proglacial dynamics are not relevant for this study. You should focus on the experiments on the glacier. The tracer injections in the proglacial stream are, from my point of view, just valuable for calculating the rating curve. Another concern is, that you use the same tracer (of course earlier on the experiment days) for this purpose. But how can you be sure that there is still tracer in the proglacial stream system influencing your dye experiment on the glacier? The same holds for your differing injection points on the glacier. A multiple tracer-multiple injection points design at differing times throughout the ablation period would have been more straight forward.
- *When doing tracer experiments in the proglacial stream we ensured that values returned to base level between experiments. While it was possible to use Uranine for some experiments on the glacier (when the dye was not exposed at the surface for very long) we could not use this in the stream as it photo-decays very quickly. Also, saying that multiple tracers and multiple injection points throughout the ablation season would have been more straightforward is an over-simplification. Rabots glaciär is a remote site, which requires helicopter transport of equipment, and we simply did not have the resources to do these experiments with increased frequency, or to have people over there for the full summer. Furthermore the proglacial dynamics are important not only for producing a rating curve, but are necessary to monitor in a catchment for which a large proportion of discharge can be attributed directly to melting of snow and ice. So we do not feel that including the proglacial experiments detracts from the rest of the manuscript.*

Why were the injections points in the lower parts of the glacier and not in the source zone of pollution? You mentioned one sentence at the end of the manuscript. But this explanation is very important and should be provided in the methods section.
- *We did conduct more than one dye trace as close to the source zone as possible, with the necessity of flowing meltwater (A5, A6 and A7), but only one (A7) gave us a dye return due to*

issues with the fluorometer (Table 1). By conducting dye injections across the altitudinal extent of flowing meltwater on the glacier we are able to gain insight into the properties of the glacier hydrological system within different altitudinal ranges. Conducting dye traces from within the source zone provides an average of hydrological system conditions across the full extent of the ablation zone, and can be better interpreted in conjunction with other experiments. We have now discussed this within the "dye tracing experiments" methods section.

The quality of the figures must improve significantly! Figures 1 and 2 could be combined. Figure 3 dies not cover the whole study period. Furthermore, the experiment days could be highlighted here and you could think about including here the turbidity information too. Figure 5 is the key graphic of this study. I could barely read the axis titles and the legends. Why is there no dye recovery curve for the first three experiments (according to Table 1 there was some tracer return)? Please mention in the caption that scaling of the y-axis is varying among the plots. Why did you show the regression lines with such a weak R2 in Figure 7? You talk about differing regime types, highlight them.
- *Figures 1 and 2 remain separate because the background image in figure 1 does not extend down to the gauging station location, and thus in addition to cluttering a single figure with too much information, it looks untidy when combining these figures. Figure 3 does cover the whole study period. The dates for discharge measurements were wrong in the manuscript and have now been changed. This also explains why there is no dye recovery curve for the first three experiments; they were done before discharge monitoring began, and average measured (rating curve calculated) discharge for the period of the experiment is necessary to calculate dye recovery. Turbidity is not included in figure 3 as it was not measured continuously throughout this period; only when the fluorometer was turned on. With regards to figure 5, the Discussions page format is landscape with a square content area, which means that figure 5 looks much smaller than it will do in the final portrait format of HESS; but font size has now been increased where possible. Information has also now been added in the caption to figure 5 to point out the variation in y-axis scaling. Figure 7 has now been updated to remove the regression lines and colour-code the meltwater flow regimes.*

Figure 8 is used as kind of a perceptual graphic for characterizing the main flow units of the glacier. However, it seems that this information is from another study (Jennings et al., 2014). So pleased include your additional findings about the flow system in this figure, otherwise it is useless.
- *Jennings et al. (2014) is not about Rabots glaciär; we were simply using this as an example from elsewhere. However, this section and figure 8 have been removed in an effort to streamline the discussion.*

There are lots of speculations (e.g. Page 13721, Lines 18ff) throughout the paper. The discussion about the turbidity dynamics in the context of the relevant literature is vague due to the limited dataset. Furthermore, I think the definition of the four meltwater flow regimes is a bit vague and the identification of an increasing drainage efficiency during the melting season is nothing new. Using actual dates and DOY in parentheses would be better for more clarity at some points (e.g. Page 13716, Line 23).
- *The flow regimes have now been discussed in more detail, in line with the reviewer's comments and additional input from Mauri Pelto. Prior to the methods section of the paper we talk about dates in terms of days and months so that the reader can put our study into a temporal context. Figure 3 is introduced in section 3.2, and marks where the days of year fall in terms of calendar months, so from this point onward we chose to refer to days of year.*

The authors try to explain the results of the experiments in separate sections. From my point of view, it would improve the paper to discuss the findings combined with a focus on the internal flow system of the glacier.
- *In line with comments from reviewer 2 the results and discussion have now been split. More emphasis has been added on the four identified flow regimes within a new sub-section, which should improve the readers understanding of the system.*

<u>Technical Corrections</u>

Page 13712, Line 1: I would suggest including the specification (kerosene) of the pollutant for more clarity.
- *Edited in manuscript.*

Page 13713, Line 12: Year of used reference is wrong. According to the references list it should be 2010. Please check.
- *Changed in reference list.*

Page 13715, Lines 8-11: This sentence would better fit into the conclusions section.
- *This sentence is here to help put the work into a regional context.*

Page 13716, Line 8: Methods instead of Method
- *Agreed – this had been changed during typesetting.*

Page 13717, Line 1: rating
- *Changed in text.*

Page 13717, Line 3: include here the information, that you did this for varying water levels in order to get the rating curve.
- *Added to text.*

Page 13717, Line 4: Better title would be "3.3 Dye tracing experiments"
- *Changed in manuscript.*

Page 13717, Line 6: 17 experiment? From Table 1, I just can see 15.
- *Yes, this was a typing error – changed in text.*

Page 13717, Line 17: What is this residence times?
- *Clarified within the text.*

Page 13722, Line 9: Please mention the rainfall event at this point too.
- *Added to text.*

Page, 13722, lines 25 and 26: The term return curves here is misleading. Breakthrough curve may be more appropriate.
- *Changed in text.*

Page 13723, Line 5: Why is this breakthrough curve not shown?
- *I have now added the curve to Figure 5 to aid comparison.*

Page 13723, Line 28: …of dye injection instead of for experiments.
- *Changed in text.*

Page 13724, Line 2: for instead of of
- *I don't agree with this – 'of' is correct here.*

Page 13725, Line 22: found instead of find
- *The rest of the text in lines 20 to 25 is in present tense, so 'find' is correct.*

Page 13727, Line 5: I did not see this 60% reduction in Table 2. The values there are ranging between 5 and 71%
- *We stated that there is a 60% reduction over time with the exception of experiment A7, so 60% is correct.*

Page 13727, Line 22: efficient
- *Un-italicized.*

Better quality of the mathematical equations (e.g. Page 13719, Eq. 3 and Eq. 5)
- *We will ensure that quality of equation formatting in the final paper is acceptable.*

Response to anonymous referee 2:

<u>General Comments</u>

A general issue I have with this study is the general link drawn between the dye tracing, transport properties and pollutants. It goes a bit circular for me since assumptions about transport are made when analyzing dye tracing which is then invoked to infer something about transport for pollutants. Are the "transport properties" derived here any different what would be estimated for any glacier where a dye tracer study was performed? If the answer is "yes" then a much better job bring that front and center (along with motivating why such different estimates are needed). If the answer is "no", the study should be conceptualized to focus in on what is learned from the dye tracing for glacier hydrology. Consider the first sentence of the conclusion: "The results of dye tracing experiments provide a new and unique insight to the internal hydrological system of Rabots glaciär, and offer an understanding of the pathways and transit times of pollutants through the glacier." I would tend to agree with the first part of this statement but not necessarily the second part. If you remove the words "of pollutants" from the second part, it is simply a restatement of the first part. What have you learned explicitly about movement of pollutants in this system? My point is that I am guessing (and hoping) there is enough novelty here to motivate the study without what can currently be considered a tenuous connection to pollutants and/or transport.
- *This study was funded as part of a monitoring programme following the plane crash, and the motivation for conducting dye tracing tests was to use these as a proxy for flow of pollutants in solution through the hydrological system, as stated as the first main objective in the introduction. So to say that there is a tenuous connection does not reflect the motivation of the study. This study was of course also very useful in helping us better understand the hydrology of Rabots glaciär, as has been described in the paper. What's different about this study in comparison to others applying dye tracing to the hydrological system of glaciers, is*

that a significant amount of fuel was spilled at this site. Thus the study not only has implications for glacial hydrology of Arctic valley glaciers, but also for the environment and for users of water resources in the Rabots glaciär hydrological catchment. We have edited the manuscript to present what we hope is a more balanced discussion of these issues.

Along similar lines, the introduction lacks clear structure and tends to mix site descriptions and even some apparent results and discussion of the study (see P13714L17). A better job of putting the study in context must be done. It would also be nice to have a fundamental research question or hypothesis in there that the study seeks to test. I think that would really help pull things together and clarify the scope of the study. Where I primarily get confused is the introduction's tendency to focus on the storyline of the fuel spill while the study itself is focused on dye tracing experiments over the glacier. I fail to see the connection between about P13713L19 through P13714L16 and the main objectives outlined at the end of the introduction. Is the only connection that the dye tracing was carried out as part of the post-spill monitoring? That is rather weak.
- *The introduction has been edited to better reflect the scope of the study, and the structure of the revised manuscript.*

This mixing of information and tendency towards a lack of clarity comes up throughout. The results and discussion section is a good example (there are even some methods mixed up in there – see P13724L4). To help streamline the presentation and clarify the central findings, these sections really should be separated (and thinned to some extent). I will admit that I get lost in the wealth of information and results and interpretation being put forward in the current section. The text essentially jumps in and out of detail making it difficult to follow. My read is that many hypotheses are developed rather than tested through these results. In addition, even in this current results and discussion section, there is referencing back to pollution spreading that apparently comes out of nowhere. By separating into a tradition results section and discussion section, you can include some sub-sectioning and present, for example, a discussion on "Implications for transport in glacier environments" where you discuss clearly the fate of the hydrocarbons in this landscape based on you experimental results. In addition, there could be a sub-section where you present and develop your meltwater regimes and how the glacier hydrology changes over time (P13725L25). This would really lend clarity to what was learned from the experiments. I would also recommend a simple schematic outlining the shifts and changes under the different time periods to allow syntheses across the many strands of evidence (it would help the reader). As currently presented, it is hard to distill out what is learned in this experiment and the extent to which it advances our understanding of glacier hydrology.
- *The results and discussion have now been split as you suggest, with new sub-sections specifically discussing the identified flow regimes, meltwater storage, and implications for the pollution. Figure 7 has been edited to include storage retardation, providing a graphical illustration of how the flow regimes hold up between each set of variables, and figure 6 has been edited to highlight clustering of values within flow regimes 3 and 4. We also include a new figure 8 which summarizes the characteristics of each flow regime. The paper has been restructured such that the methods and results focus only on the glacier hydrology; as you indicated before, these results can stand on their own. Instead we come back to the implications of our findings for pollution in the Rabots glaciär catchment in a final sub-section within the discussion.*

With regards to the estimates and modeling made, it would be relevant to include some uncertainty and error estimates. There are many assumption made and many inherent

calibrations. Given the error potential in your experimental design (both in the sampling equipment and frequency), what are the implications for your final estimates? Given that you have several dye injections and have mixed different resolutions and types of sampling, you have a rather natural setup to explore the inherent role of error and uncertainty. Further, it could be interesting when considering the potential for distributions of travel times and (for example) small but really fast preferential flow pathways relative to the slower average bulk. Such an analysis can only serve to make your results and conclusion more robust!
- *This is outside the scope of this paper, which is already rather long. In fact, error estimates of dye tracing applied to glaciers is something that, to my knowledge, has never been looked at in detail, but would certainly warrant a standalone study.*

Last, the conclusion section needs trimmed. Much is just repetition of previous statements. Further, it gets rather far off topic when speculating about further experiments and pollution transport (especially given the current study). Also, the last paragraph is not connected to the rest of the study. Specifically, I do not see how this research offers unique insights about pathways. The insights gained here would be fundamentally the same as insights gained about pathways for transport from any glacial dye experiments.
- *Yes, the insights gained here about pollution transport are the same as for dye transport, as we are using the dye as a proxy for pollutants in solution. However, these experiments allow us to evaluate how rapidly pollutants could move through the system from the source zone, and, importantly, give us an insight into storage of pollutants that have entered the hydrological system of the glacier. These are important considerations for us when evaluating the longevity of contamination at this site. The conclusion has been trimmed and reworded where appropriate. We have also revised our use of the word pathway throughout the manuscript, as what we are actually evaluating is the form and efficiency of the system, since we can't "see" the flow pathways.*

Specific/Editorial Comments

Title: Should have a 'the' in front of 'hydrocarbon-polluted'? Also, polluted is a relative term here since you are comparing (I assume) to a pristine background with no hydrocarbons. Also, see my general comments regarding transport. Would it make more sense to have a title like "Dye tracing to determine flow properties of Rabots glaciär, Kebnekaise, Sweden"?
- *The glacier is definitely polluted with regards to background level, but we have shreamlined the title somewhat.*

P13712L7: Probably should be 'potential flow pathways'
- *Agreed. Changed in text.*

Abstract: Many uses of the word 'efficient' suggesting it almost as a quantifiable aspect (here and throughout the entire manuscript). Some of these vague qualifiers must either be defined as measureable quantities and/or backed up with numbers.
- *In glaciology we commonly talk about the 'efficiency' of the hydrological system as derived from the results of tracer experiments and the form of breakthrough curves. See recent studies by Cowton et al. (2013) and Willis et al. (2012) which use the same language, and follow the same equations as have been applied here. A definition of what we interpret to be efficient has been added to the dye breakthrough results section of the manuscript.*

P13713L17: Should be 'provides'

- *Changed in text.*

P13713L26: Change ‘it’ to ‘the kerosene jet fuel’
- *Edited in text.*

P13714L25: Sure sounds like you know a lot about the glacier and flow pathways after I read the site description! I can imagine there are glaciers out there that we know nothing about.
- *Rabots glaciär has received relatively little attention in comparison to Storglaciären, and almost no previous work has been conducted on the hydrological system, so I think what we have written here is fair.*

P13716L19: Personally, I would change ‘ca.’ to ‘about’ or ‘around’ (here and everywhere)
- *This is a personal preference, and I would prefer to keep it as c. (or ca. as the typesetters have amended it to in the Discussions paper).*

P13716L20: Remove ‘for’
- *Removed from text.*

P13716L23: Why switch over to what I am assuming are days of the year? Up until now you were using dates.
- *Dates were used at the beginning of the manuscript to help put the study into a temporal context for the reader without having to refer to a Julian Day calendar. Figure 3 shows where the months fall during our study period in comparison to days of year. We believe it is easier to refer to days of year when discussing the data and results.*

P13717L17: This would be the initial estimated residence time since you would not know the residence time until you ran the experiments, correct?
- *The sampling rate was the highest we could use in the fluorometer, which we later determined was above the recommended value from Nienow et al (1996).*

P13718L11: Would be good to see how the essentially calibrated variable Q compared with the observed.
- *That’s the issue, and why we let Q vary. Q is not directly observed, rather derived from measured stage based on the rating curve. Since we do not know for certain that we caught the highest and lowest levels of stream flow throughout the season, we cannot assume that “observed” Q is correct.*

P13719L13: How does one account for error sources in such a calculation? It looks like any model-observed disagreement is chalked up as a retardation factor. Could disagreement be due to errors either in the sampling/analysis? This estimate sounds like a fudge factor to get around the physics mismatch of the advection-dispersion assumption.
- *The nature of the advection-dispersion model, which produces a roughly symmetrical curve, assumes that the model can reproduce flow through a simple channel, but the slower drop in dye concentrations typical of the falling limbs of glacier system dye breakthrough curves means that a storage retardation component is missing from this simple model. See Willis et al. (2009).*

P13720L7: Keep an eye on significant digits in your discharge (and all) estimates. In this paragraph you are bouncing around with the number of decimals shown.

- We have now gone through the whole manuscript and edited to make sure this is consistent to two significant figures and/or two decimal places where appropriate.

P13720L14: Clarify if you intend stream water temperature or air temperature.
- We have now clarified that we are referring to air temperature throughout this paragraph.

P13721L1: Why is this definition coming here? It is odd and even an over simplified definition for hysteresis neglecting system memory.
- Hysteresis is not a concept often considered within glaciology, in comparison to hydrology, so we thought it appropriate to define it here to cater for a broad spectrum of potential readers. I think that stating that stating that it is dependent on whether the independent variable is increasing or decreasing does address system memory at a basic level.

P13721L6: The hysteresis 'implies' and you 'infer'
- Edited in text.

P13721L9: Again, you are just giving a graphical definition of hysteresis here.
- This sentence rather describes what clockwise hysteresis means in the context of the system we are considering.

P13722L10: Are there any records of rainfall or precipitation activity in the region in this period to support your hypothesis?
- Yes. See Figure 3 (we now direct the reader to this within the manuscript).

P13722L13: "Easy mobilisation of sediments at Rabots glaciär may be a source of pollution spreading and transport, where pollutants sorb to sediment particles" This is a general statement that could be made about almost any system. What pieces of your results specifically support this?
- This statement has now been removed.

P13723L5: What does it mean to be in agreement in terms of "form" of breakthrough?
Should this be quantified?
- This refers to the shape of the breakthrough curve. We have since added the manually-derived breakthrough curve for experiment A7 to figure 5 to aid comparison.

P13723L12: What does efficient mean here? Fast?
- Changed to 'rapid' in the text.

P13723L15: Were these really measured? I would have thought they were calculated or inferred.
- You're right. Changed to 'calculated'.

P13723L23: Now you are using '~' instead of 'ca.' or 'about'. Pick one and be consistent.
- Changed to c.

P13723L26: From your naming convention, this should be "Rabots glaciär's"? It gets confusing with the mixed language naming.
- Changed in text.

P13273L27: Change to “observed” and keep in past tense for results. This will be easier and clearer if you split the section (see general comments).
- Changed in text.

P13724L24: You have switched to ‘en/subglacial’ from ‘en- and subglacial’. Be consistent here and everywhere.
- Ok, changed to ‘en-‘ instead of ‘en’ throughout.

P13725L5: This does not fit here and is just a generic definition.
- Removed from manuscript.

P13725L20: Here is a definition of what you intend with efficiency. Be more specific throughout.
- A definition has now been added at the start of the section about dispersivity.

P13726L11: Change to ‘m s -1’. Check throughout.
- Changed in manuscript.

P13276L24: By efficient you mean low dispersion?
- See definition added in section 4.5.

P13727L3: What are return curves?
- Changed to ‘breakthrough’.

P13727L5: “showed” (see line 8 on the same page). The tense shifting is awkward.
- Changed in text.

P13727L23: Does efficient now mean single peaked or rather narrow crested?
- See definition added in section 4.5.

P13728L12: Yes, they may but did they?
- We can’t see inside the glacier so don’t know for sure, but it is very likely. However, we have removed this section (and figure 8) from the revised manuscript in an effort to streamline the discussion section.

P13728L20: I think you are highlighting my previous comment that it is difficult to isolate the role of processes and errors through this storage retardation estimate approach.
- It could be this, or it could be that the dye is stored within the braided proglacial system, and mobilised when discharge/stage increases, resulting in unreliable quantification of dye return. Some additional discussion of this has now been added in the manuscript.

P13728L24: “The results of dye tracing experiments provide a new and unique insight to the internal hydrological system of Rabots glaciär, and offer an understanding of the pathways and transit times of pollutants through the glacier.”Well, I would agree with the first part of this statement but not necessarily the second. If you remove the word “pollutants” from the second part, it is simply a restatement of the first part. What have you learned explicitly about movement of pollutants in this system? See general comments.
- Ok, I understand what you mean. In line with revising the manuscript following your general comments, the word “pollutants” has been removed here, and the conclusions revised.

Response to comments from Mauri Pelto

I had a few comments on what I thought was an excellent paper. Sorry I did not see this paper in time to post them. They all focus on one small section that I think is so informative, and just am looking for ways it can be more so.

Clason et al (2015) provide an exceptionally detailed field investigation of meltwater flow timing through a polythermal alpine glacier. This commentary focusses on just one important aspect of the paper, that deserves more attention, the dispersivity regimes, section 4.4.

The authors identify four key flow regimes, this is an important identification. For each flow regime it would be helpful to have a consistent identification of the comparative dispersivity, throughflow velocity and drainage system efficiency. The shared attributes for each regime should be identifiable in Figure 5 and Table 2. This is the case for Regime 1 and Regime 3. Regime 3 in particular have such narrow and symmetric breakthough curves. For regime 2 there is only a single example, which is fine. For Regime 4 the throughflow velocity and delay in discharge are strikingly similar for the two experiments, however, the dispersivity and recovered dye percentage are strikingly different. What then summarizes the flow regime conditions for Regime 4? Are experiments A5 and A6 likely indicative of the Regime 4 as typified by A7 with a very long delay and lack of dye recovery?

Given the changes in the regime noted how does each regime and then the combination of them as described influence the exponent in the power law for Table 3 and Figure 6? The authors note "a much larger exponent for en/subglacial flow through Rabots glaciär may indicate that discharge is accommodated by an increase in hydraulic gradient within the system due to backing up of water, and by decreasing sinuosity, as proposed both for Storglaciären." This suggests high water pressure exists even late in the season, for the A3 and A7 injection locations, but not simultaneously for A1, A2 and A4. Given the narrow time frame between experiments A1-A4, comment on that the regimes are not distinct temporally but spatially, since A3 is so close to A1 and A2.

Thanks, hope these are a help, either way I will look forward to the final paper.

- We have edited figure 7 to include further comparison between dispersivity, elevation, throughflow velocities and storage retardation (dye recovery could only be calculated for the August experiments when contemporaneous measurement of discharge was available, so we do not include this in the graphical comparison). Flow regimes 3 and 4 are now highlighted within figure 6. An additional schematic has been added (Figure 8) to better illustrate and summarize the characteristics of each flow regime. We have also commented on the distinction between regimes 3 and 4, and what this could imply about the system at these locations.

References:

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Dye tracing ~~for investigating~~to determine flow ~~and transport~~ properties of hydrocarbon-polluted Rabots glaciär, Kebnekaise, Sweden

Abstract

Over 11000 L of ~~hydrocarbon pollution~~kerosene was deposited on the surface of Rabots glaciär on the Kebnekaise Massif, northern Sweden, following the crash of a Royal Norwegian Air Force aircraft in March 2012. An environmental monitoring programme was subsequently commissioned, ~~including water, snow and ice sampling. The scientific programme further~~ includ~~ed~~ing a series of dye tracing experiments during the 2013 melt season, conducted to investigate the transport of ~~flow pathways for~~ pollutants through the glacier hydrological system. This experimental set-up provided a basis from which we could~~,~~ ~~and to~~ gain new insight to the internal hydrological system of Rabots glaciär. Results of dye tracing experiments reveal a degree of homogeneity in the topology of the drainage system throughout July and August, with an increase in efficiency as the season progresses, as reflected by decreasing temporary storage and dispersivity. Early onset of melting likely led to formation of an efficient, discrete drainage system early in the melt season, subject to decreasing sinuosity and braiding as the season progressed. Four distinct meltwater flow regimes are identified to summarize the temporal and spatial evolution of the system. Analysis of turbidity-discharge hysteresis further supports the formation of discrete, efficient drainage, with clockwise diurnal hysteresis suggesting easy mobilisation of readily-available sediments in channels. Dye injection immediately downstream of the pollution source zone ~~revealed~~ reveals prolonged storage of dye followed by fast, efficient release. Twinned with a low dye recovery, and supported by sporadic detection of hydrocarbons in the proglacial river, we suggest that meltwater, and thus pollutants in solution, may be released periodically ~~from this zone of the glacier hydrological system~~through an efficient, and likely pressurized hydrological system within the upper reaches of the glacier. ~~The here identified dynamics of dye storage, dispersion and breakthrough indicate that the ultimate fate and permanence of pollutants in the glacier system is likely to be governed by storage of pollutants in the firn layer and ice mass, or within the internal hydrological system, where it may refreeze. This shows that future studies on the fate of hydrocarbons in pristine, glaciated mountain~~

~~environments should address the extent to which pollutants in solution act like water molecules or whether they are more susceptible to, for example, refreezing into the surrounding ice, becoming stuck in micro-fractures and pore spaces, or sorption onto subglacial sediments.~~

1 Introduction

Dye tracing provides an opportunity to study the otherwise unseen drainage system inside and underneath glaciers. Measuring the rapidity and pattern of dye emergence, as well the quantity of dye recovered at the proglacial outlet, can provide important insight into the form and efficiency of the glacier drainage system. Dye tracing has been applied successfully in the alpine environment in several studies and has contributed substantially to understanding of subglacial drainage systems, for example, Storglaciären in the Kebnekaise mountains in northern Sweden (e.g. Seaberg et al., 1988; Hock and Hooke, 1993), glaciers in the European Alps (e.g. Nienow et al., 1998), the High Artic (e.g. Bingham et al., 2005) and, more recently, the Greenland Ice Sheet (Chandler et al., 2013; Cowton et al., 2013). More generally, the number of extensive dye tracer studies of glaciers is still limited (Willis et al., 2012), and basic unresolved issues remain in understanding the temporal and spatial variability of glacial drainage systems, the extent of efficient drainage, and the morphology of englacial and subglacial drainage.

~~The distribution of advective travel times derived from tracer experiments also provide an essential basis in quantifying large-scale transport and attenuation-retention processes that govern catchment-scale contaminant spreading (Darracq et al., 2010; Destouni et al., 2010).~~ The here considered Rabots glaciär in Kebnekaise mountains was subject to a large spill of hydrocarbons, originating from a crash of a Royal Norwegian Air Force Lockheed Martin C-130J Super Hercules aircraft on 15th March 2012. The aircraft crashed into the western face of Kebnekaise, approximately 50 m below the mountain ridge, during a military exercise. Of the initial 14100 L of kerosene jet fuel on board at take-off, an estimated minimum of 11100 L was sprayed over the snow and ice-covered mountain environment, together with 50 L of hydraulic oil and 170 L of turbo oil (Rosqvist et al., 2014). Some of ~~it~~ the kerosene was subsequently swept down and buried on Rabots glaciär by a large snow avalanche along with the wreckage. Wreckage debris was also found on neighbouring Storglaciären and Björlings glacier, but the majority was deposited on Rabots glaciär, which was not subject to immediate clean-up or decontamination of fuel due to the hazardous nature of the impact site and the large volume of snow affected.

~~Extensive plumes of dissolved contaminants often develop down-gradient of hydrocarbon source zones, as for instance shown through monitoring of numerous spills in industrial areas (e.g., Jarsjö et al., 2005). To understand potential adverse environmental impacts of the Kebnekaise accident, it is imperative to characterise the transport of dissolved constituents with glacial meltwater through Rabots glaciär. In addition, hydrocarbons that remain after volatilization (e.g., Jarsjö et al., 1994) may also move with water in free (non-dissolved) phase; for instance, relatively light hydrocarbon mixtures like kerosene will float on top of water-saturated zones (e.g., Schwille, 1981).~~ Hydrocarbons were detected in the snow pack of the pollution source zone on Rabots glaciär (Figure 1) and at sporadic intervals in the proglacial river system during the 2013 melt season (Rosqvist et al., 2014). This provides evidence for active advection of pollutants through the glacier system during 2013, the ~~rapidity and transit pathways~~properties of which are discussed here following the application of dye tracing. The ~~pathways for~~ transport of hydrocarbon pollution through a full glacier system ~~have~~ has never before been studied, and thus dye tracing is imperative if we are to understand anything about advective travel times of pollutants in a glacier system.

Here, we present the results of dye tracing experiments conducted as part of a monitoring programme on Rabots glaciär during the 2013 melt season, commissioned by the National Property Board of Sweden (Statens Fastighetsverk). The main objectives are: (i) provide new temporal and spatial information on the previously little-studied hydrological system of Rabots glaciär, (ii) identity distinct meltwater flow regimes within the glacial hydrological system based on analytically-derived properties of dye returns ~~to use dye breakthrough curve characteristics to determine pathways for transport of hydrocarbon pollution from the source zone to the proglacial environment,~~ and (iii) to apply dye breakthrough characteristics to evaluation of the transport of hydrocarbon pollution from the source zone to the proglacial environment~~ provide new temporal and spatial information on the previously little-studied hydrological system of Rabots glaciär, and (iii) obtain and interpret the discharge and turbidity of Rabots proglacial river system~~.

Rabots glaciär has received relatively little attention compared to neighbouring Storglaciären, which is the best studied glacier in Sweden (e.g. Stenborg, 1965, 1969, 1973; Nilsson and

Sundblad, 1975; Schytt, 1981; Holmlund, 1988; Jansson, 1996; Schneider, 1999; Glasser et al., 2003, Fountain et al., 2005), and an understanding of its hydrological system has been extremely limited until now. The majority of dye tracing experiments in moulins on Storglaciären have been conducted in the lower ablation zone below a riegel in the bedrock topography (e.g. Seaberg et al., 1988; Hock and Hooke, 1993; Kohler, 1995), as the overdeepened trough upstream of the riegel results in a largely englacial drainage system (Hooke et al., 1988; Pohjola, 1994; Fountain et al., 2005) and an absence of surface meltwater input points~~; during fieldwork on Rabots glaciär moulins have been found distributed over a greater altitudinal range.~~ Dye tracing experiments conducted in crevasses, moulins or boreholes at elevations above the riegel ~~under~~ on Storglaciären have thus been limited and produced very attenuated, or, in some cases, no ~~return of~~ dye return (Hooke et al., 1988; Jansson 1996). The greater variability in subglacial topography beneath Storglaciären, compared to Rabots glacär (Björnsson, 1981) results in differences in surface to bed connections. On storglaciären input points are highly localized to the riegel area, whereas on Rabots glacär points are scattered across a large portion of the glacier surface. For evaluating pollution transport through Rabots glaciär it is thus clear that the knowledge from Storglaciären is not sufficient or even applicable. The results presented below thus provide new insights into the hydrology of Rabots glaciär with the aim of providing a basis for monitoring pollution transport. The study also highlights the contrasts between the two glaciers and the effect of basal topography on the hydrological system and system behaviour.

2 Site description

Rabots glaciär is a small, 3.1 km^2, polythermal valley glacier, situated on the western side of Kebnekaise (2099 m a.s.l.) in sub-Arctic Sweden (Figure 1). The glacier extends from 1848 m a.s.l. at its highest point down to 1111 m a.s.l. at the snout, with an average slope of 11.5°. The maximum recorded Little Ice Age (LIA) extent of Rabots glaciär dates to 1910, as captured in photographs taken in 1910 by Enqvist (Brugger and Pankratz, 2014). In comparison to neighbouring Storglaciären, which has been characterised by a relatively stable terminus position in the last c. 20 years, significant retreat of Rabots glaciär from its LIA maximum and thinning continues due to its longer response time to climatic changes (Brugger, 2007). Radio-echo sounding conducted in 1979 found that Rabots glaciär had a maximum ice thickness of 175 m, with an average of 84 m (Björnsson, 1981). It also revealed that the subglacial topography underneath Rabots glaciär is gently sloping with no pronounced overdeepenings. This is in strong comparison to Storglaciären, for which the bed is characterised by several subglacial overdeepenings and a pronounced bedrock riegel (Björnsson, 1981). One may then expect Rabots glaciär to exhibit different hydrological behaviour due to the less complex nature of topography beneath the glacier. Meltwater at the terminus of Rabots glaciär leaves primarily through two proglacial streams. The high turbidity of the northernmost of these streams indicates that it has much more interaction with bed sediments than its relatively clear southern counterpart. The proglacial environment is characterized by several braided systems that travel through an overridden inner moraine and a pronounced terminal moraine (Karlén 1973). The overall hydrological catchment size amounts to 9 km^2 with an ice covered area of 33%.

3 Methods

3.1 Meteorological data

Meteorological data were recorded between April and September 2013 by an automatic weather station at 1355 m a.s.l. on Rabots glaciär. Meteorological variables, including air temperature and precipitation, were measured every minute and the mean of these measurements stored at 15 minute intervals. Air temperature was measured at 0.5, 1 and 2 m above the surface using HygroClip T/Rh sensors and recorded as both transient and average values. Total precipitation was recorded by a Young unheated tipping bucket rain gauge.

3.2 Proglacial river discharge

River gauging was conducted at a stable bedrock location in the proglacial river during the 2013 melt season, c. 1.5 km downstream of the glacier terminus (Figure 2). This location permitted convergence of the proglacial outlets and ~~for~~ measurement at an area of constrained flow downstream of the numerous braided systems operating between terminal moraines. Measurements of ~~both~~ river stage and of air and water pressure were conducted between days ~~181~~ 203 and ~~249~~248 (Figure 3). Stage was measured by a SR50A sonic ranging sensor and pressure was recorded by HOBO U20 data loggers. Discharge time series were constructed from both relative gauging height (every 15 min) and relative water pressure (every 10 min) based on a rating~~s~~ curve produced by relating measured stage and pressure to discharge calculated for repeated rhodamine dye tracings (D1 to D5; Table 1) representative of varying water levels in the proglacial river.

3.3 Dye tracing experiments

Field campaigns targeting glacial hydrology were conducted during July and August 2013, during which ~~17~~ 15 dye tracing experiments were ~~conducted~~ carried out to quantify transit times and ~~pathways~~ and flow properties ~~for~~ of meltwater flow through crevasses in the upper reaches of the glacier, moulins throughout the ablation zone (Figure 2), and in the proglacial river (Table 1). Experiments were conducted across the altitudinal range of flowing surface meltwater on the glacier in order to understand how the en- and subglacial hydrological system changes down-glacier. Dye injections in the pollution source zone alone provide only an average of en-/subglacial conditions across the full altitudinal extent of the ablation zone. A known quantity of Rhodamine water tracer 20% solution (RWT) was used in the majority of dye tracer experiments, with Uranine (Na Fluorescein) 33.3% solution used when simultaneous experiments were desired. Uranine is susceptible to photo-degradation, so injection was conducted as close as safely possible to the englacial opening to reduce time exposed to sunlight. Dye was injected into flowing water in every case, upstream of open crevasses and moulins. Emergence of the dye~~s~~ was measured using both manual sampling and automated detection methods, and for all experiments, the sampling rates for both automatic and manual detection were less than 1/16 of the measured residence time (the time between dye injection and maximum detected concentration)~~,~~, ~~suggested~~as suggested by Nienow et al. (1996) to be ~~a~~ the ~~maximum acceptable measurement period~~maximum acceptable period for accurate estimation of dispersivity. ~~.~~

For automated detection of dye emergence, an Albillia GGUN-FL30 field fluorometer was stationed in the proglacial stream (Figures 1 and 2), and was monitored at regular intervals to check the stability of the sonde within the stream. The FL30 is a flow-through fluorometer with a minimum detection limit of c. 2×10^{-11} g mL^{-1}, and allows detection of 3 separate tracers simultaneously, in addition to measuring turbidity and water temperature, at a sampling rate up to 2 s. In order to establish the preferential flow pathway for meltwater originating at the hydrocarbon source zone, water samples were taken manually in both of the main streams emerging from the glacier front (Figures 1 and 2) during experiment A7. The samples were analysed for fluorescence with a Turner Designs AquaFluor handheld fluorometer, set up for Rhodamine WT at a minimum detection limit of 0.4 ppb. Based on calibration of the instruments (for a 100 ppb solution), fluorescence was converted to dye return concentration to produce breakthrough curves for each experiment. These dye returns were subsequently used to calculate the throughflow velocity, dispersion coefficient, dispersivity, storage retardation and dye recovery for each successful experiment (Table 2).

3.4 Dye breakthrough analysis

For each dye return a modelled concentration-time (breakthrough) curve was calculated using an advection-dispersion model (Brugman, unpublished; Seaberg et al., 1988; Cowton et al., 2013), at a temporal resolution of 30 s. The concentration of dye is represented as c at time t, where V_0 represents the volume of injected dye, and Q is discharge (m^3 s^{-1}), which was allowed to vary freely in order to produce a best fit to the measured breakthrough curve for each experiment (Willis et al., 1990; 2009). Variation of Q was permitted even for the August experiments where Q was measured, since discharge does not remain constant throughout an experiment, and to account for error associated with deriving discharge from a rating~~s~~ curve:

$$c(t) = \frac{v}{Q}\frac{V_0}{\sqrt{(4\pi D t)}}\exp - \frac{(x - vt)^2}{4Dt} \tag{1}$$

Throughflow velocity, or transit speed, v (m s^{-1}), for each experiment is calculated as:

$$v = \frac{x}{t_m} \tag{2}$$

where the transit distance x (m) is the straight line distance between the injection point and sampling location, and the residence time t_m (s) is the time between dye injection and peak concentration. This value was corrected for travel time in the stream during the August experiments to account for the different positioning of the FL30 fluorometer in July and August.The dispersion coefficient D (m^2 s^{-1}) in equation (1) indicates the rate at which dye spreads within the glacier hydrological system (Willis et al., 2009). The variable t_j represents the time taken until half of the peak concentration on the rising (t_j = t_1) and falling limb (t_j =

t_2) of the measured dye return curve. The equation is solved iteratively for t_m for both $t_j = t_1$ and $t_j = t_2$ until the equations converge to obtain the same value of D (Seaberg et al., 1988):

$$D = \frac{x^2 (t_m - t_j)^2}{4\, t_m^2 t_j \ln\left(2\sqrt{\frac{t_m}{t_j}}\right)} \tag{3}$$

Dispersivity, d (m), is further calculated to describe the spreading rate of dye relative to the transit velocity through the glacier, providing an inference for transit route complexity (Seaberg et al., 1988; Willis et al., 1990):

$$d = \frac{D}{v} \tag{4}$$

Temporary storage of dye in the glacier results in elongation of the falling limb of the modelled return curve, and is not accounted for in the advection-dispersion model (Seaberg et al., 1988; Schuler et al., 2004; Willis et al., 2009). To examine this, storage retardation, *SR*, is thus quantified as the percentage area difference under the measured and modelled falling limbs (Nienow 1993; Schuler 2002; Cowton et al. 2013). The higher the *SR*, the lower the fit between the modelled and measured curve, thus the higher the temporary storage. Further, dye recovery, *W* (g), describes the weight of dye which passed through the fluorometer during an experiment, where *dt* is the logger interval in seconds, and *Q* is the average measured discharge for the duration of the experiment:

$$W = \sum_{t=1}^{n} c\, Q dt \tag{5}$$

The percentage dye recovery can then be expressed as a percentage, $W\%$, where W_0 is the initial mass of the injected tracer:

$$W\% = 100\,\frac{W}{W_0} \tag{6}$$

4 Results ~~and discussion~~and interpretation

4.1 Proglacial d~~D~~ischarge

Discharge in the proglacial river remains relatively small throughout the measurement period, with an average of 1.~~79~~ 8 $m^3\ s^{-1}$. In response to relatively high air temperatures in July (Figure 3), discharge reaches a maximum of 3.9~~2~~ $m^3\ s^{-1}$ on day 212, before experiencing a step-wise decrease to a period of steady discharge averaging around c. 1.3 $m^3\ s^{-1}$ from day 221 to day 227. The second half of August is characterised by discharge fluctuating by c. 2 $m^3\ s^{-1}$ in response to rainfall events and periods of higher air temperatures. Average discharge continues to fall into September. The diurnal cycle of discharge lags that of air temperature, with peak discharge occurring daily on average c. 2 h after peak recorded air temperature, representing the response time of the river to ablation and transit of meltwater through the glacier. The amplitude of the diurnal discharge cycle decreases throughout the melt season (Figure 3).

4.2 Turbidity

The turbidity of the proglacial river system, recorded in Nephelometric Turbidity Units (NTU), was not measured continuously throughout the season, but measured contemporaneously with dye fluorescence at the river gauging station (Figure 2) during 6 out of 10 days in August 2013. Average peak discharge occurs within one hour of average peak turbidity (Figure 4C), indicating that mobilisation of sediments leads discharge. Hysteresis, a behaviour for which a value of the dependent variable can vary for a given value of the independent variable depending on whether the independent variable is increasing or decreasing (Hodgkins 1996), is observed both at the diurnal scale and at a multi-day scale, over a period of 10 days (Figure 4A and B). At the diurnal scale, hysteresis was observed only in a clockwise direction, while a figure-eight was produced at the multi-day scale, encompassing both clockwise and anticlockwise behaviour (Figure 4a, b). Clockwise hysteresis implies that peak diurnal turbidity leads peak diurnal discharge, as exemplified in Figure 4C, such that for equivalent discharge values on the rising and falling limbs of the hydrograph, turbidity is higher on the rising than the falling limb (Hodgkins, 1996). In this context, clockwise hysteresis can be interpreted as easy mobilisation of fresh sediment flushed out from channel beds and margins, followed by an exhaustion of sediment supply (Hodgkins, 1996; Singh et al., 2005; Pietron et al., in review). Given the short period of time over which turbidity was recorded at Rabots glaciär it is not possible to investigate multi-day evolution of sediment mobilisation over the melt season. However, within a limited period of 10 days we observe a figure-eight clockwise/anticlockwise hysteresis loop (Figure 4B). Conversely to clockwise behaviour, anticlockwise hysteresis implies that the peak in diurnal discharge leads the peak in diurnal turbidity, indicating that sediments are not as easily mobilised.

Diurnal observations of hysteresis in the proglacial river of Rabots glaciär were entirely clockwise, and are therefore comparable with the largely clockwise hysteresis recorded by Singh et al. (2005) for Gangotri Glacier in the Himalayas. Data collection in the Gangotri study, however, extended over a full melt season, much longer than our 10 day, non-continuous measurement period. One may compare further with observations of hysteresis at Scott Turnerbreen in Svalbard (Hodgkins, 1996), for which a progressive change in hysteresis from clockwise to anticlockwise was observed during the melt season. Scott Turnerbreen is a ‘cold-based’, non-temperate glacier (Hodgkins, 1996), while Rabots glaciär is polythermal, and because of differences in the glacier hydrological system, particularly at the bed, this may explain why we do not see anticlockwise diurnal hysteresis in the late melt season at Rabots glaciär. Temperate Bench glacier in Alaska has also been observed to produce clockwise behaviour, including during two flood events (Riihimaki et al., 2005). The anticlockwise pattern observed between days 220 and 222 (Figure 4B) follows a period of increased temperatures between days 217 to 219 (Figure 3). Sediments within the glacier system may have been flushed out, and sourced from higher elevation, during this period due to higher melt rates, followed by a period of sediment exhaustion. This may have been exacerbated by the prevalence of silty sediments subject to strong cohesion in the glacier forefield, reducing the possibility for sediment mobilisation. The sharp increase in turbidity in the Rabots glaciär proglacial stream during day 228 is likely a reflection of a peak in temperature, combined with a precipitation event, lagged by a peak in discharge (Figure 3). We hypothesise that increased temperature, and thus increased meltwater availability, combined with a precipitation event (Figure 3), may have permitted extension of the network of subglacial conduits during this period, allowing access to a fresh sediment supply at the glacier bed, as also observed by Riihimaki et al. (2005).

4.3 Dye breakthrough

Results from calculation of analytical dye return parameters for each experiment are listed in Table 2, along with discharge calculated for each experiment based on measurements in the proglacial river. Measured breakthrough curves are illustrated for each successful glacier dye tracing experiment in Figure 5. Experiments A5 and A6 were unsuccessful due to failure of the fluorometer data logger. Modelled breakthrough curves and dye recovery are also depicted for the August experiments. Visual interpretations of the breakthrough curves reveal that there is a decrease in curve width with progression of the season, as well as an increase in symmetry. All curves except J1 and J2 exhibit a smooth asymmetric form, as observed elsewhere (e.g. Seaberg et al., 1988, Willis et al., 1990; Cowton et al., 2013), and are characterised by clear single peak ~~return~~ breakthrough curves. ~~Return~~ Breakthrough curves J1 and J2 are more complex in form, with longer falling limbs that do not reach base level values before the end of the experiments. These curves are also characterised by a higher degree of noise, likely due to low dye recovery. Breakthrough curves characterised by rapid dye return, with a narrow, single-peaked form are interpreted to be indicative of an efficient sub-/englacial drainage system (Hubbard and Nienow, 1997). This interpretation can be further strengthened by values of low dispersivity and storage, and fast throughflow velocities, indicative of high throughput of water in a channelized system (e.g. Cowton et al., 2013).

Experiment A7 was monitored simultaneously by both automated fluorescence detection and manual water sampling in both major proglacial outlets. The dye emerged only in the southernmost, less turbid proglacial outlet. The dye breakthrough curve derived from the analysis of water from manual sampling was in accordance with that from automated detection using the FL30 both in terms of form and emergence time. That manually-analysed breakthrough curve was, however, characterised by increased noise due to turbidity, which is not corrected for in manual sampling. The breakthrough curves of experiment A7 represent meltwater flow from as close to the source zone as was possible with the condition of flowing water for injection. Both curves reached their peak c. 14 hours after injection, after c. 12 hours with no dye signal. The residence time, form of the breakthrough curve, and emergence of the dye in only one (less turbid) proglacial outlet indicates temporary storage followed by ~~an~~ a rapid ~~efficient~~ release of meltwater, with little interaction with the bed substrate.

4.4 Throughflow velocities

~~Measured~~ Calculated throughflow velocities are an average of flow velocities within the englacial and subglacial drainage system between the injection site and detection point. Throughflow velocities range from 0.04 to 0.28 m s^{-1} for the glacier-based experiments (Table 2), which fall within the range of values previously inferred from experiments on Storglaciären (Seaberg et al., 1988; Hock and Hooke, 1993). A threshold of 0.2 m s^{-1} is proposed by Theakstone and Knudsen (1981) and Nienow (2011) to distinguish between fast and slow flow. Willis et al. (2009) propose a similar threshold for fast flow, considering velocities of <0.05 m s^{-1} as slow, ~~~~~ c. 0.1 m s^{-1} as moderate and >0.15 m s^{-1} as fast. Flow velocities above the proposed thresholds for fast flow have traditionally been interpreted as indicative of channelised transport while flow velocities below the threshold indicate distributed water routing (Seaberg et al. 1988; Willis et al. 1990; Cowton et al. 2013). Throughflow velocities in ~~the~~ Rabots glaciär's proglacial river reached a maximum of 0.58 m s^{-1}. We observed no clear relationship between velocity and elevation ~~for experiments~~of dye injections on the glacier, or between velocity and time into the season. The lowest values of throughflow velocity were calculated for experiment A7, and we hypothesise that they are representative of a relatively long period of initial storage before more rapid flow following a sudden meltwater release.

Following Leopold and Maddock (1954), the relationship between throughflow velocity and discharge can be expressed as a simple power function. There is a positive correlation between throughflow and discharge both for glacier-based dye returns (R^2 = 0.65) and proglacial returns (R^2 = 0.27) at Rabots glaciär (Figure 6). The results of this study are compared against those from neighbouring polythermal Storglaciären (Seaberg et al., 1988) and temperate outlet glacier Midtdalsbreen, Norway (Willis et al., 1990) in Table 3. Seaberg et al. (1988) differentiated between proglacial and sub/englacial flow, while Willis et al. (1990) divided recorded discharge two tributary systems T1 and T3, which were interpreted as draining two different glacial hydrological systems. In the proglacial system of Rabots glaciär, velocity increases with the 0.6 power of the discharge. The associated multiplier is lower than that calculated for Sydjokk, one of the proglacial rivers of neighbouring Storglaciären (Seaberg et al., 1988), such that velocity through Sydjokk is 2.8 times larger than for the Rabots glaciär proglacial river. The braided nature of the Rabots proglacial river as it navigates through the proglacial outwash plain and terminal moraines may explain this difference.

The exponent of the en- and subglacial drainage is also significantly higher in this study compared with Storglaciären and Midtdalsbreen, while the multiplier is in the same order as that for Midtdalsbreen. For a given discharge, the velocity of water flowing en- or subglacially or both in Rabots glaciär is thus 2-3 times lower than Midtdalsbreen, and 13 times lower than Storglaciären. The much larger exponent for en-/subglacial flow through Rabots glaciär may indicate that discharge is accommodated by an increase in hydraulic gradient within the system due to backing up of water, and by decreasing sinuosity, as proposed both for Storglaciären (Seaberg et al., 1988) and T1 of Midtdalsbreen (Willis et al., 1990), rather than through changes in cross-sectional channel area. Cowton et al. (2013) and Nienow et al. (1998) state that a flow in a channelised system is expected to be 1-2 orders of magnitude higher than in a distributed system. We do not see this order of magnitude difference in our data (Table 2), or an increase in velocity over time, which is likely a product of early onset melt and development of the drainage system.

4.5 Dispersivity

~~Dispersivity is a measure of the extent to which dye spreads out relative to the speed at which it travels downstream with meltwater (Willis et al., 1990).~~ Low dispersivities (< 5 m) are typically indicative of efficient water routing, and high values of dispersivity (> 20 m) have been associated with drainage of decreased efficiency, possibly due to distributed drainage system form (Nienow et al. 1998; Bingham et al. 2005; Willis et al. 2009). Water that is stored either supraglacially or englacially may also increase the rate of dispersivity (Fountain 1993; Schuler et al. 2004); for example through buffering of meltwater flow in snow and firn layers, or storage in englacial fracture networks. From visual interpretation of the return curves (Figure 5) the elongation of the falling limb in relation to the rising limb decreases with time into the melt season. This is supported by falling values of both dispersivity and the dispersion coefficient (Table 2), with the exception of experiment A7, for which dispersivity experiences a fourfold increase compared to experiment A4. A7 was the highest elevation at which dye was injected, which likely explains the increase in dispersivity despite being late in the melt season (Figure 7B).

We interpret the decrease in dispersivity over time (Table 2) as an increase in drainage system efficiency, despite a general decrease in discharge and its diurnal cyclicity after peak discharge in late July (Figure 3). ~~Furthermore, we~~We find no significant relationship between dispersivity and either velocity or elevation (Figure 7A, B), with R^2 values of 0.19 and 0.35 respectively. We do, however, find a positive relationship between dispersivity and storage retardation (Figure 7C), with an R^2 value of 0.85, relating the spreading rate of dye to the temporary storage of dye in the system. ~~; instead we propose that the relationship between velocity and dispersivity is indicative of four distinct meltwater flow regimes. The first regime encompasses J1 and J2, which are characterised by both high dispersivity and relatively high throughflow velocities despite occurring earliest in the field season, and are representative of lowest drainage system efficiency. The velocity values may imply channelised but sinuous flow, possibly impeded by interaction with basal sediments down the relatively long flow pathways, resulting in noisy, multi-peaked breakthrough curves (Figure 5). The second regime is represented by experiment J3, which depicts a large decrease in dispersivity, 17 days after experiment J2. The breakthrough curve in this case is single-peaked, but the elongated falling limb implies increased dispersivity, which may be explained through continued sediment interactions. The northernmost stream through which the July experiments likely exited the glacier is turbid, supporting extensive interaction with the bed sediments.~~

~~The third regime contains experiments A1, A2 and A4, which are the three lowest elevation experiments, characterised by low dispersivities and throughflow velocities in excess of 0.18 m s^-1^. Flow through these moulins has the shortest travel pathway through the system, aided by the largest increase in drainage system efficiency due to the low elevation and time into the melt season. Experiments A3 and A7 fall under flow regime four, characterised by low throughflow velocities, and relatively low dispersivity in comparison to the July experiments. The form of the breakthrough curves for A3 and A7 is single-peaked, which, in addition to the relatively low dispersivities, supports channelised flow, despite low throughflow velocities. Injection point A3 is located just upstream of the moulins used for experiments A1, A2 and A4 (flow regime three). Despite this, there is a considerably increase in residence time for~~

~~experiment A3; at least 2.5 hours longer than for flow regime three. The residence time of A7 is the longest of the successful experiments, at c. 14 hours, characterised by a broad yet single-peaked return curve (Figure 5). We interpret the behaviour displayed by the return curve of experiment A7 as reflecting sub/englacial meltwater storage followed by periodic release through an efficient system. This explains the long residence time and the unrepresentatively low throughflow velocities. Experiments A5 and A6 (Figures 1 and 2) did not produce a dye breakthrough, indicating residence times longer than our detection period during day 222 of c.11 hours. Temperature, precipitation and discharge were all relatively low during this period (Figure 3), perhaps indicating refreezing in the glacial hydrological system at the relatively high elevation of c. 1350 m a.s.l..~~

~~4.6 Meltwater storage and flow constraints~~

~~The temporary storage of dye can be viewed as an influencing factor on dispersion, which manifests itself as an elongation in the falling limb of modelled return curves (Figure 5; Willis et al., 2009; Cowton et al., 2013). With the exception of experiment A7, results show a 60% reduction in storage retardation from glacier-based tests over time (Table 2). The largest storage values correspond with the more complex breakthrough curves returned from the July experiments, relating to high dispersivity and a less efficient drainage system. As throughflow velocities showed no increase with time, we propose that the reduction in storage retardation over time relates to increasing efficiency, and decreasing sinuosity, rather than evolution from a true distributed system to a channelised system, which had likely already formed due to early onset of melt in 2013. Similar behaviour was reported by Cowton et al. (2013) for the Leverett Glacier, southwest Greenland. Low dye recovery was calculated for experiments A2 and A4. Uranine was used as a tracer in these experiments, thus low dye recovery is likely accounted for by photochemical decay of the dye between emergence from the glacier terminus and detection by the fluorometer downstream.~~

~~Combined with a very low dye recovery (Table 2), the mechanism of storage and release proposed to explain the return curve of experiment A7 may be indicative of storage in the englacial system (Fountain, 1993; Cowton et al., 2013). In this case, quantities of the injected dye, which become dilute as more meltwater enters the system, may be released periodically, resulting in a low dye recovery and a smooth, single-peaked, efficient breakthrough curve with an elongated falling limb. This hypothesis is strengthened by the 5% storage retardation~~

~~calculated for automated sampling during the experiment (Table 2). Sporadic detection of hydrocarbons in the proglacial system (Rosqvist et al., 2014), rather than continuous emergence of pollutants, further attests to periodic release of meltwater and pollutants stored within the en-/subglacial hydrological system. The stream in which dye emergence from experiment A7 was detected manually has a very low turbidity in comparison to its northern counterpart, which allows us to further hypothesize that meltwater emerging in the southern proglacial outlet interacts with the bed to a lesser degree, and is possibly routed downstream for a long distance within the englacial system. Low recovery rates for both manual and automated sampling of experiment A7 may be exacerbated by refreezing of dye onto the ice since dye detection continued overnight, during falling temperatures and very low discharge. The surface structure of Rabots glaciär is characterised by three major flow units emerging from the accumulation zone (Figure 8), which partition the tongue longitudinally and create structural independence between units (Jennings et al., 2014). Structural weaknesses and longitudinal foliation along the boundaries of these flow units may provide a pathway for englacial meltwater flow, in addition to supraglacial flow as described by Hambrey (1977). The presence of flow units may thus constrain the flow of meltwater and pollutants from the source zone to the south side of the glacier, emerging in the southernmost proglacial outlet, as observed for experiment A7.~~

~~With the exception of experiment D1, proglacial dye experiments for production of a ratings curve resulted in recovery of at least 78% of the dye, with sorption to sediment particles likely to contribute to this result. Storage retardation varied between 18% and 38%, and for three of these experiments storage retardation exceeded the percentage of dye that was not recovered. This overestimation of storage retardation may be attributed to the advection-dispersion model, which was adjusted to the best fit of the model efficiency criteria, and for which only the falling limb of the breakthrough curve is considered.~~

5 Discussion

5.1 Meltwater flow regimes

We propose that clustering of the values of the variables throughflow velocity, storage retardation, elevation, discharge, and dispersivity (Figure 6, Figure 7), in concert with breakthrough curve form (Figure 5), indicates the existence of four distinct meltwater flow regimes, as summarized in Figure 8. Regime 1 encompasses experiments J1 and J2, which are characterised by both high dispersivity, relatively high throughflow velocities despite occurring earliest in the field season, high storage retardation and are representative of relatively low drainage system efficiency. The velocity values may imply channelized but sinuous flow, possibly impeded by interaction with basal sediments down the relatively long flow pathways, resulting in noisy, multi-peaked breakthrough curves (Figure 5). Regime 2 is represented solely by experiment J3, which depicts a large decrease in dispersivity and an increase in system efficiency, seventeen days after experiment J2. The breakthrough curve for J3 is single-peaked, but the elongated falling limb illustrates temporary storage of dye, albeit less than for regime 1. The northernmost stream through which the July experiments likely exited the glacier is very turbid. Interaction with basal sediments may contribute to the high storage retardation characteristic of regimes 1 and 2.

Regime 3 contains experiments A1, A2 and A4, which are the three lowest elevation experiments, characterised by low dispersivity, low storage retardation and high throughflow velocities (Figure 7, Figure 8). Flow through these moulins has the shortest travel pathway through the system, with dye injected at relatively low elevation, late into the ablation season, into a system relatively high in discharge. Breakthrough curves in regime 3 are all single peaked and very narrow (Figure 5), which combined with the characteristics summarized in Figure 8, indicate a high degree of drainage system efficiency. Experiments A3 and A7 fall under flow regime 4, characterised by low throughflow velocities, low storage retardation, low dispersivity and relatively low discharge. The form of the breakthrough curves for A3 and A7 is single-peaked but, which supports channelized flow, despite low throughflow velocities. Injection point A3 is located just up-glacier of moulins used for experiments A1, A2 and A4 (regime 3). Despite this, there is a considerable increase in residence time for experiment A3; at least 2.5 hours longer than for experiments within regime 3. The residence time of A7 is the longest of the successful experiments, at c. 14 hours, characterised by a broad yet single-peaked breakthrough curve (Figure 5).

When comparing selected attribute pairs for experiments A3 and A7 (Figure 8), the only variable for which clustering is not produced is elevation, suggesting a long operating pathway between these two injection points (Figure 2). We interpret the behaviour depicted by the breakthrough curve of experiment A7 as reflecting sub/englacial meltwater storage followed by periodic release through an efficient system, addressing contemporaneous long residence time, low throughflow velocities, low dye recovery, yet a single-peaked dye breakthrough curve with low storage retardation. Only six days past between the experiments in regime 3 and experiment 7, and experiment A3 was conducted on the same afternoon as experiment A4 in regime 3, thus the distinction between these two regimes is spatial, and not temporal. Analysis of throughflow velocities against discharge (Figure 6, Table 3) indicated that backing up of water may occur within the hydrological system of Rabots glaciär to accommodate discharge within a system decreasing in sinuosity with distance downstream, resulting in an increased hydraulic gradient with elevation. We may then expect that a pressurized system still existed late into the season at the locations of experiments in regime 4, resulting in the observed low throughflow velocities (Figure 8), while dye injections within regime 3 entered a low pressure system with fast meltwater flow.

5.2 Meltwater storage

The temporary storage of dye can be viewed as an influencing factor on dispersion (Figure 7e), which manifests itself as an elongation in the falling limb of modelled breakthrough curves (Figure 5; Willis et al., 2009; Cowton et al., 2013). With the exception of experiment A7, we observe a 60% reduction in storage retardation in glacier-based dye tracer tests over time (Table 2). The largest storage values correspond with the more complex breakthrough curves from the July experiments, relating to high dispersivity and a less efficient drainage system. As throughflow velocities showed no increase with time, we propose that the reduction in storage retardation over time relates to increasing efficiency, and decreasing sinuosity, rather than evolution from a true distributed system to a channelized system, which had likely already formed due to early onset of melting in 2013. Similar behaviour was reported by Cowton et al. (2013) for the Leverett Glacier, southwest Greenland. Low dye recovery was calculated for experiments A2 and A4. Uranine was used as a tracer in these experiments, thus low dye recovery is likely accounted for by photochemical decay of the dye between emergence from the glacier terminus and detection by the fluorometer downstream.

Combined with a very low dye recovery (Table 2), the mechanism of storage and release proposed to explain the return curve of experiment A7 may be indicative of storage in the englacial system (Fountain, 1993; Cowton et al., 2013). In this case, quantities of the injected dye, which become dilute as more meltwater enters the system, may be released periodically under pressure, resulting in a low dye recovery and a broad, single-peaked breakthrough curve. This hypothesis is strengthened by the 5% storage retardation calculated for automated sampling during the experiment (Table 2). Sporadic detection of hydrocarbons in the proglacial system (Rosqvist et al., 2014), rather than continuous emergence of pollutants, further attests to periodic release of meltwater and pollutants stored within the en-/subglacial hydrological system. The stream in which dye emergence from experiment A7 was detected manually has a very low turbidity in comparison to its northern counterpart, which allows us to further hypothesize that meltwater emerging in the southern proglacial outlet interacts with the bed to a lesser degree, and is possibly routed downstream for a long distance within the englacial system. Low recovery rates for both manual and automated sampling of experiment A7 may be exacerbated by refreezing of dye onto the ice since dye detection continued overnight, during falling temperatures and very low discharge.

With the exception of experiment D1, proglacial dye experiments for production of a rating curve resulted in recovery of at least 78% of the dye, with sorption to sediment particles likely to contribute to this result. Storage retardation varied between 18% and 38%, and for three of these experiments storage retardation exceeded the percentage of dye that was not recovered. This overestimation of storage retardation may partly be attributed to the advection-dispersion model, which was adjusted for best fit to the measured breakthrough curve, and for which only the falling limb is considered when computing storage retardation. The presence of dye from previous experiments within the braided proglacial system, mobilised in periods of increased water level and discharge, may also affect recovery of dye, as could fluorescence from suspended sediments at the same wavelength as Rhodamine WT (Cowton et al., 2012).

5.3 Implications for transport of pollutants

~~The distribution of advective travel times derived from tracer experiments provides an essential basis in quantifying large-scale transport and attenuation retention processes that govern catchment-scale contaminant spreading (Darracq et al., 2010; Destouni et al., 2010).~~ Kerosene fractions that remain in the initial source zone (Figure 1) after surface volatilization (Jarsjö et al., 1994) can potentially dissolve into and move with meltwater through Rabots glaci~~e~~är. Extensive plumes of dissolved contaminants often develop down-gradient of hydrocarbon source zones due to advection, as for instance shown through monitoring of numerous spills in industrial areas (e.g., Jarsjö et al., 2005). The distribution of advective travel times derived from tracer experiments provides an essential basis in quantifying governing transport and attenuation-retention processes for kerosene dissolved in meltwater, which previously have been shown for large-scale spreading of dissolved contaminants in non-glaciated environments (Darracq et al., 2010; Destouni et al., 2010).

In this context, current results provide a first quantification of the large difference in transport conditions between the hydrocarbon-polluted Rabots glaciär and well-documented cases of hydrocarbon pollution in groundwater near industrial areas; most notably, the throughflow velocities (0.04 to 0.28 m s^{-1}) of Rabots glaciär are at least two orders of magnitude higher than typical advective travel times in contaminated sand aquifers of Europe (Jarsjö et al., 2005). Whereas this means risk for rapid spreading to downstream waters, the here shown existence of flow regimes characterized by relatively low tracer recovery and high storage retardation also implies that part of the dissolved kerosene may be retained in Rabots glaci~~e~~är for extended periods of time~~s~~. ~~To understand potential adverse environmental impacts of the Kebnekaise accident, it is imperative to characterise the transport of dissolved constituents with glacial meltwater through Rabots glaciär.~~ In addition, ~~hydrocarbons that remain after volatilizations~~surplus kerosene from the initial source zone ~~(e.g., Jarsjö et al., 1994)~~ may ~~also~~potentially move with water in free (non-dissolved) phase into the drainage system of the glacier; for instance, relatively light hydrocarbon mixtures like kerosene will float on top of water-saturated zones (e.g., Schwille, 1981).

5 Conclusions ~~and implications~~

The results of dye tracing experiments provide a ~~new~~ first look~~and unique insight~~ into the internal hydrological system of Rabots glaciär, ~~and~~ offering ~~an understanding of~~ a new insight into both the ~~pathways~~ properties and transit times of meltwater ~~pollutants~~ flow through the glacier. In response to an early start to the melt season, development of efficient drainage began in July, with return curves supporting increased efficiency and decreasing sinuosity throughout August. Analysis of proglacial discharge and turbidity attests further to formation of efficient subglacial drainage, with clockwise hysteresis supporting easy mobilisation of sediments readily available within channels, thus also any pollutants that may have sorbed onto sediments. More extensive dye tracing studies are necessary to explore the full seasonal evolution of the Rabots glaciär hydrological system. Nevertheless, this study provides a first insight to the drainage system topology~~, and hints towards a possible structural control on meltwater flow pathways~~, which should be explored further in future studies in concert with an investigation of the internal thermal structure of the glacier. Although limited in number, the results of these experiments suggest that in comparison to Storglaciären, the internal hydrological system of Rabots glaciär is characterised by a degree of homogeny in efficiency over a larger altitudinal extent, although constrained and divided laterally by the ice flow and structure of the glacier.

Assuming flow of pollutants in solution *with* meltwater, the delayed but efficient form of breakthrough curve A7, combined with a very low ~~percentage~~ dye return, ~~may~~ indicates that pollutants are being periodically released from an en-/subglacial store after entering the internal glacier hydrological system near the source zone. This is supported by sporadic rather than continuous detection of hydrocarbons in the proglacial river system. Experiment A7, ~~from~~ originating directly downstream of the source zone, estimates a transit time of c.15 hours for transport through the full en-/subglacial hydrological system.~~. This is likely an upper estimate for transit time as the hydrological system,~~ ~~is well-developed~~ B~~b~~y mid-August, the drainage system is well-developed, producing efficient breakthrough of dye, even for experiment A7 which originated above 1350 m a.s.l. and a very short distance from the remaining snowpack. Snow is highly permeable and thus unlikely to retain pollutants at the multi-year scale, ~~so we may expect to see storage of~~but pollutants stored within the firn layer and ice mass will continue to be ~~, through percolation or firnification, subsequently~~ released gradually by ~~melt~~ ablation processes during future melt seasons. Storage within firn and ice, ~~or~~ and within the internal hydrological system as demonstrated here, provides an opportunity for refreezing, further increasing the permanence of pollutants in the glacier system. ~~Additional study is thus necessary to determine the extent to which pollutants in solution act like water molecules or whether they are more susceptible to, for example, refreezing into the surrounding ice, becoming stuck in micro-fractures and pore spaces, or sorption onto subglacial sediments.~~

~~This research~~The results presented here offer an~~s~~ ~~a unique~~ important insight to the transport ~~pathways for~~of pollutants through a full glacier system~~,~~ contributing towards a broader analysis of the spread~~ and~~, longevity and impact of hydrocarbon pollutants in the Rabots glaciär hydrological catchment.~~. With increasing pressure on locations such as Kebnekaise from anthropogenic activity, and the environmental risks associated with these activities, our work provides a basis from which to create a new knowledge base for the analysis and action required following hydrocarbon spills in the glaciated Arctic mountain environment.~~

Author contribution

C. C. Clason led and all other authors contributed to the writing of the manuscript. Fieldwork was conducted by all authors, C. C. Clason designed the glacier hydrological experiments, C. Coch and C. C. Clason analysed the data and prepared figures.

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Table 1. Dye tracing experiments conducted on Rabots glaciär and in the proglacial river during 2013. J denotes July, A denotes August and D represents proglacial experiments.

Code	Day of year, injection time	Injection site	Tracer	Amount (mL)	Sampling (rate in min)	Dye return
J1	185, 14:47	Supraglacial stream	RWT	125	Auto (0.03); Manual (10)	Yes
J2	186, 11:37	Crevasse	RWT	245	Auto (0.03); Manual (10)	Yes
J3	203, 12:00	Moulin	RWT	250	Auto (0.03); Manual (10)	Yes
A1	220, 16:33	Moulin	RWT	150	Auto (0.5)	Yes
A2	220, 16:46	Moulin	Uranine	100	Auto (0.5)	Yes
A3	221, 14:27	Moulin	RWT	150	Auto (0.5)	Yes
A4	221, 15:26	Moulin	Uranine	100	Auto (0.5)	Yes
A5	222, 13:33	Crevasse	Uranine	200	Auto (0.5)	No
A6	222, 15:10	Supraglacial stream	RWT	125	Auto (0.5)	No
A7	227, 13:16	Supraglacial stream	RWT	500	Auto (0.5); Manual (10)	Yes
D1	220, 12:40	River	RWT	30	Auto (0.5)	Yes
D2	222, 10:49	River	RWT	30	Auto (0.5)	Yes
D3	227, 12:37	River	RWT	60	Auto (0.5)	Yes
D4	230, 12:22	River	RWT	50	Auto (0.5)	Yes
D5	230, 13:26	River	RWT	100	Auto (0.5)	Yes

Table 2. Results of dye tracing analysis from automatic sampling of fluorescence (A7* is based on manual sampling in the southernmost proglacial outlet). Here, discharge for A and J experiments is that calculated from stage recorded at the river gauging station averaged over the duration of each experiment, and for D experiments is the computed discharge based on dye tracing for production of the ratings curve.

Code	**Day of year, injection time**	**Transit distance (m)**	**Throughflow velocity (m s^{-1})**	**Dispersion coefficient (m^2 s^{-1})**	**Dispersivity (m)**	**Storage retardation (%)**	**Dye recovery (%)**	**Discharge (m^3 s^{-1})**
J1	185, 14:47	1469	0.28	24.27	86.24	70.82	n/a	n/a
J2	186, 11:37	2022	0.21	19.33	92.63	58.51	n/a	n/a
J3	203, 12:00	1165	0.15	4.04	27.79	43.86	n/a	n/a
A1	220, 16:33	655	0.25	2.84	11.59	10.71	70.70	2.01
A2	220, 16:46	703	0.19	0.81	4.25	13.84	18.79	2.00
A3	221, 14:27	829	0.06	0.19	2.89	10.78	78.69	1.61
A4	221, 15:26	488	0.23	1.22	5.34	11.03	8.77	1.60
A7	227, 13:16	2339	0.04	0.79	18.01	5.03	8.25	1.28
A7*	227, 13:16	2182	0.04	1.10	28.78	58.56	23.70	1.28
D1	220, 12:40	685	0.38	0.59	1.56	38.5	55.05	1.73
D2	222, 10:49	874	0.23	1.46	6.43	20.64	81.50	1.08
D3	227, 12:37	1237	0.36	2.91	8.11	24.77	93.52	1.28
D4	230, 12:22	408	0.24	0.10	0.41	17.80	77.69	2.36
D5	230, 13:26	1534	0.58	4.11	7.08	31.31	89.18	2.20

Table 3. Velocity-discharge analyses from Rabots glaciär, Sweden (this study), Storglaciären, Sweden (Seaberg et al. 1988) and Midtdalsbreen, Norway (Willis et al. 1990). Note that experiments were conducted over a period of two years for both Storglaciären and Midtdalsbreen.

Study	**Domain**	**Sample size**	**Multiplier**	**Exponent**	**R^2**
Clason et al. (this study)	proglacial	5	0.25	0.60	0.27
Clason et al. (this study)	sub/englacial	5	0.02	3.44	0.65
Seaberg et al. (1988)	proglacial	13	0.69	0.27	n. a.
Seaberg et al. (1988)	subglacial (Sydjokk)	6	0.26	1.00	n. a .
Willis et al. (1990)	sub/englacial (T1)	5	0.06	1.00	0.44
Willis et al. (1990)	sub/englacial (T3)	8	0.04	0.60	0.10

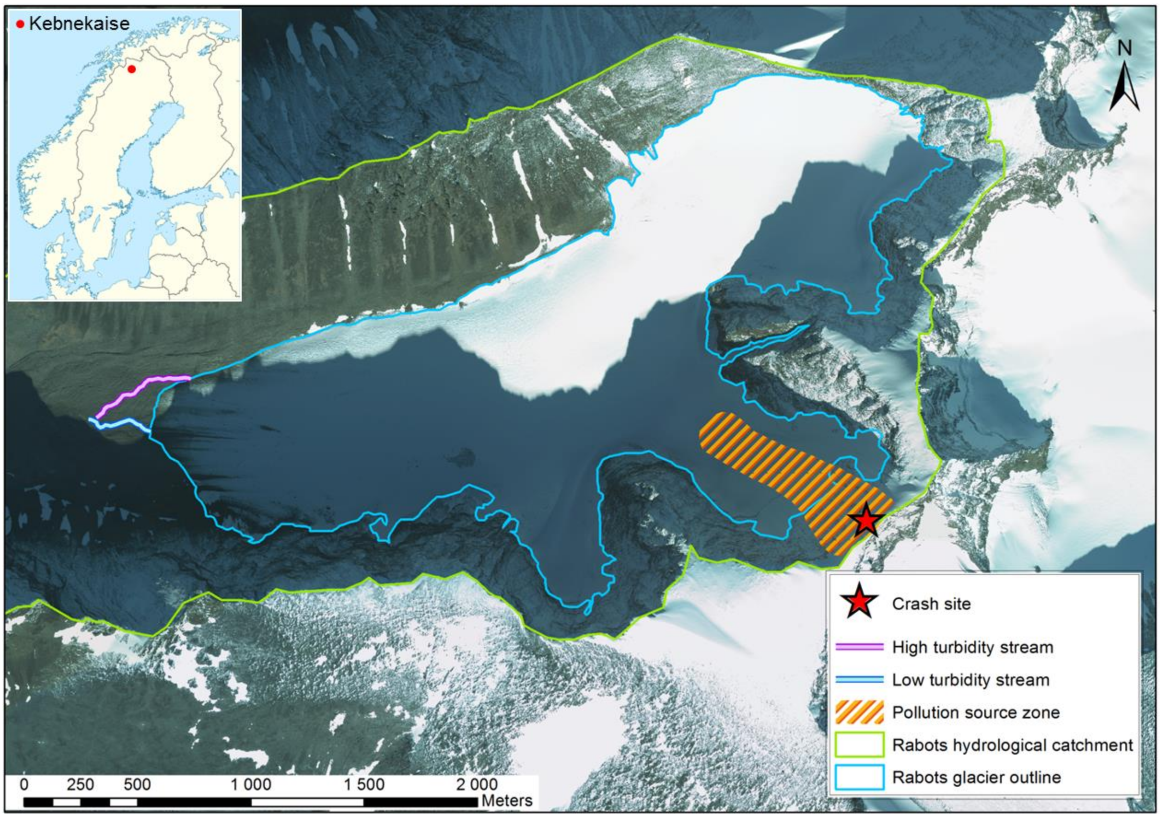

Figure 1. Rabots glaciär with glacier extent marked in blue and the hydrological catchment in green. The site of the plane impact is depicted by the red star, and the orange spotted area represents the estimated area of the initial source zone of hydrocarbon pollutants. The background image is an orthophoto captured in 2008 by Lantmäteriet.

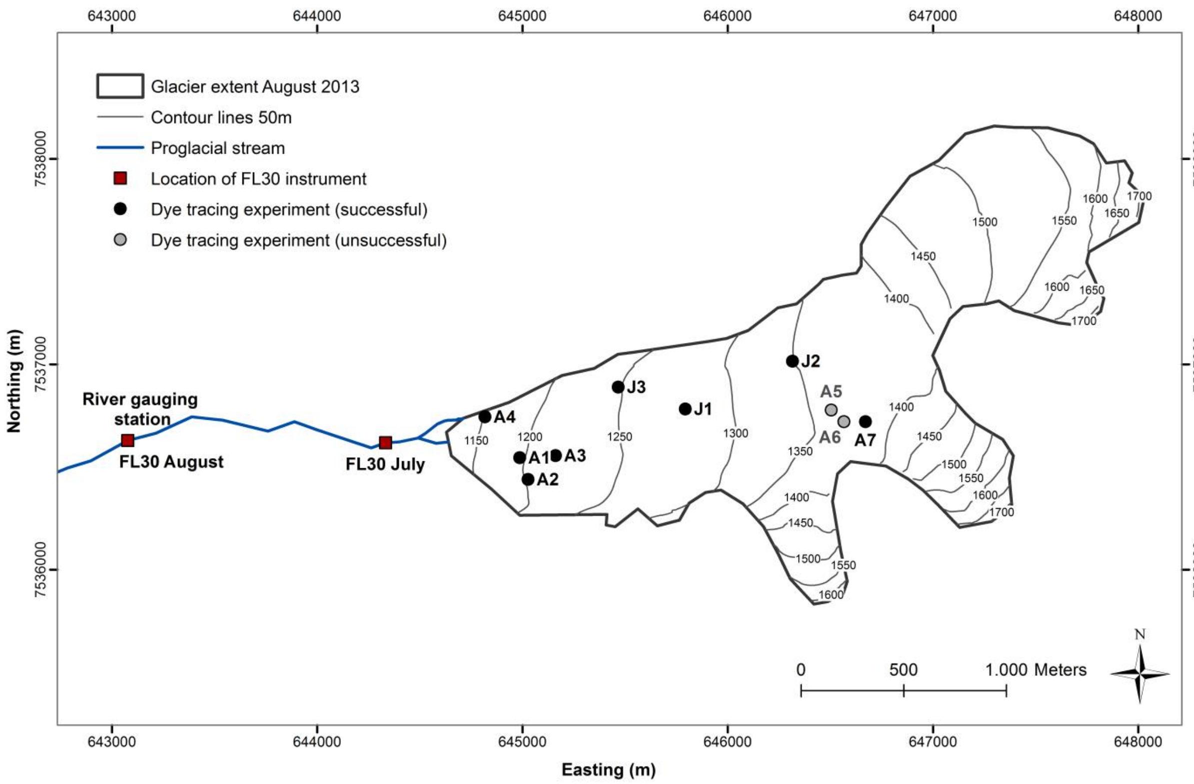

Figure 2. Locations of glacier-based dye tracing experiments during 2013.

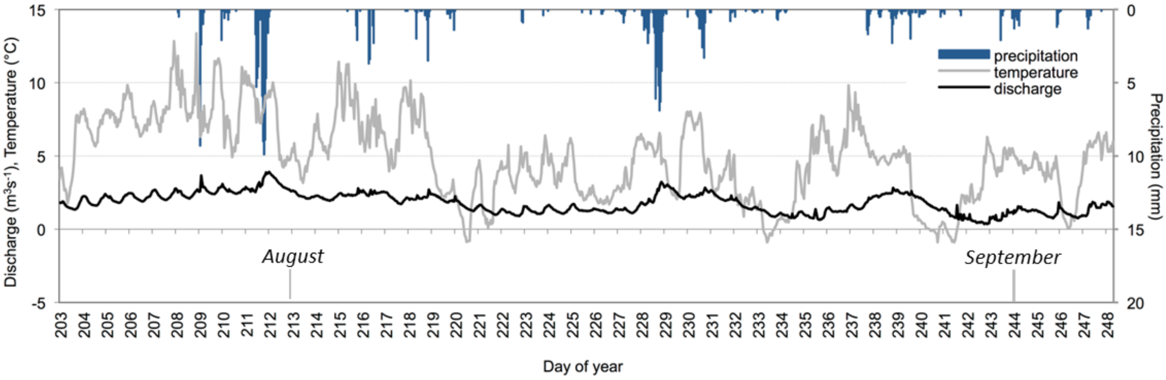

Figure 3. Measured 2 m temperature, precipitation and calculated discharge during summer 2013 (days span 22nd July – 5th September).

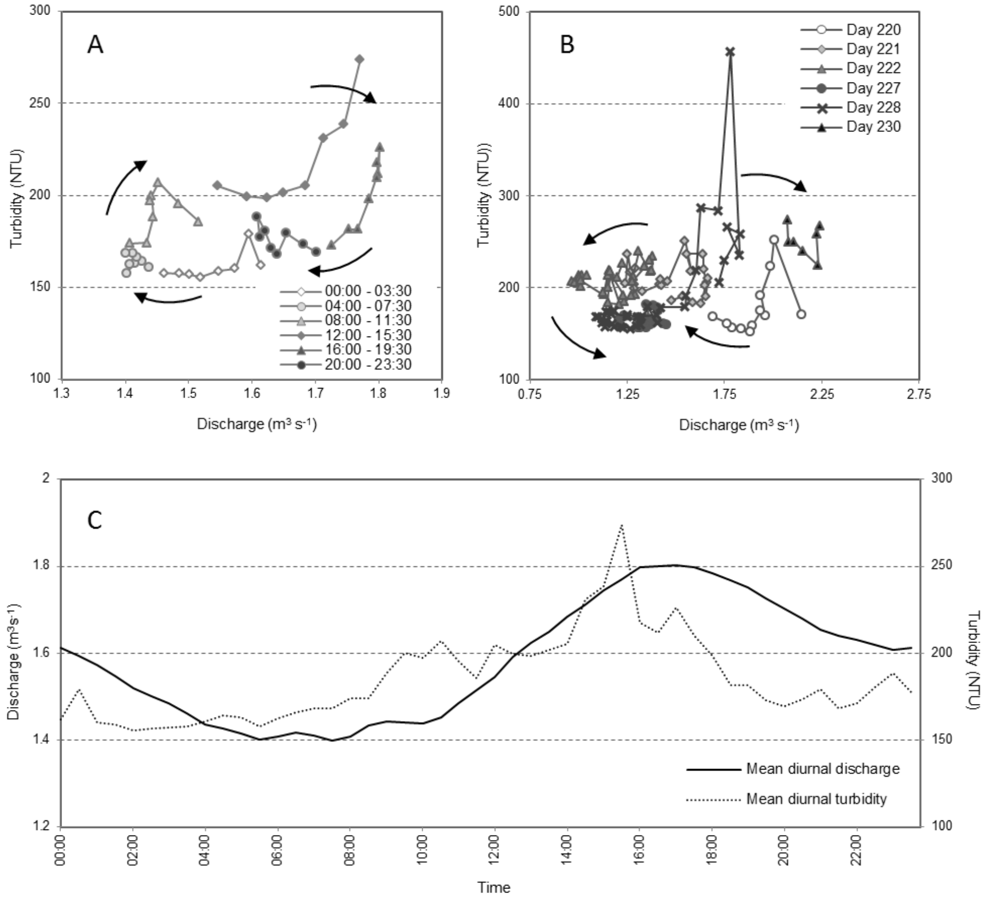

Figure 4. A) Diurnal turbidity, averaged at 30 minute intervals across all measurement days, plotted against mean diurnal discharge, B) all available measurements of turbidity (30 minute intervals) plotted against discharge, and C) diurnal cycle of discharge and turbidity averaged at 30 minute intervals for all available measurements between days 220 and 230.

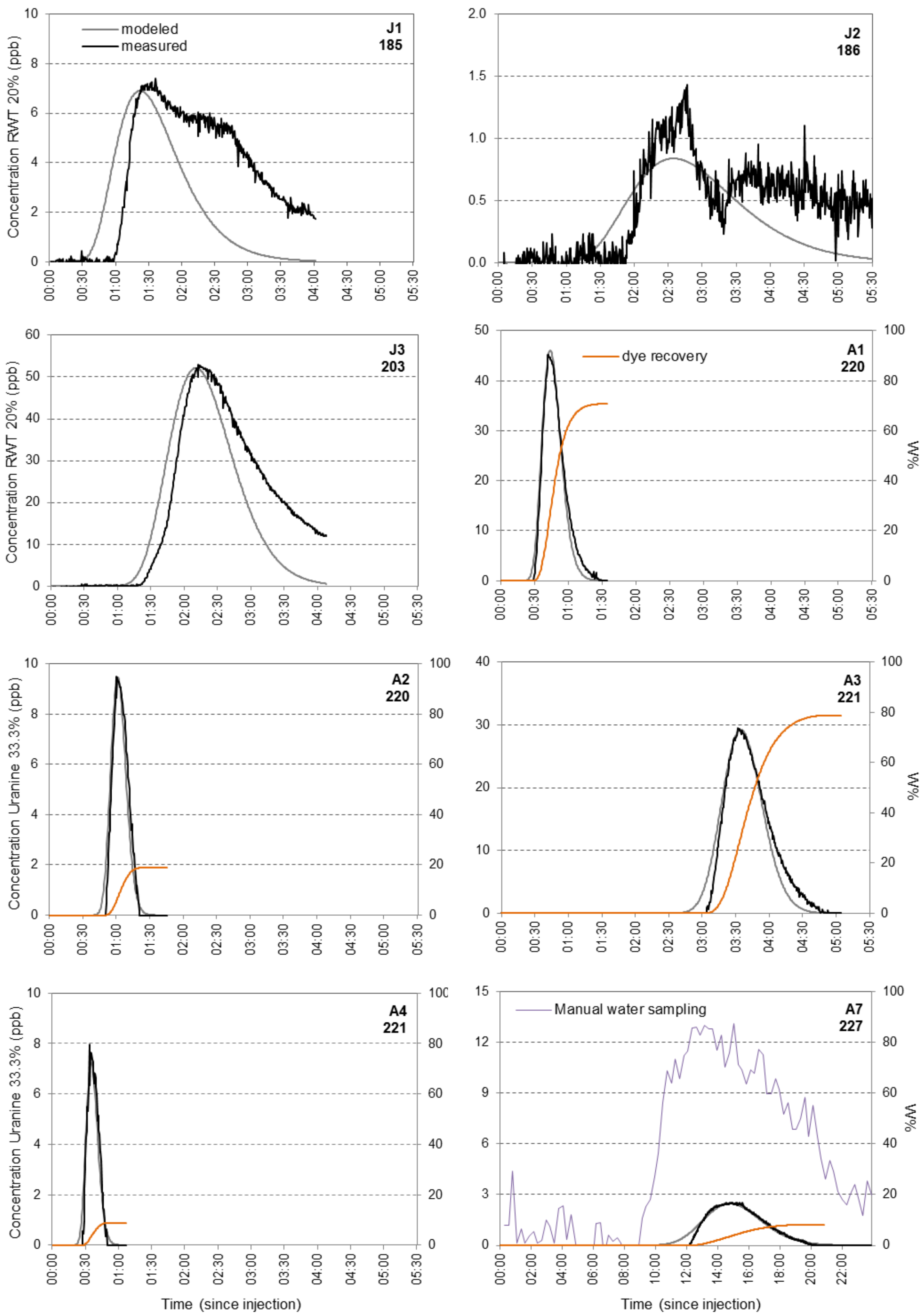

Figure 5. Modelled and measured dye breakthrough curves, including dye recovery for the August experiments. Note that the x-axis for experiment A7 differs from the others due to the particularly long dye return time, and the y-axes are scaled differently for each experiment in order to best view the form of the breakthrough curves.~~.~~

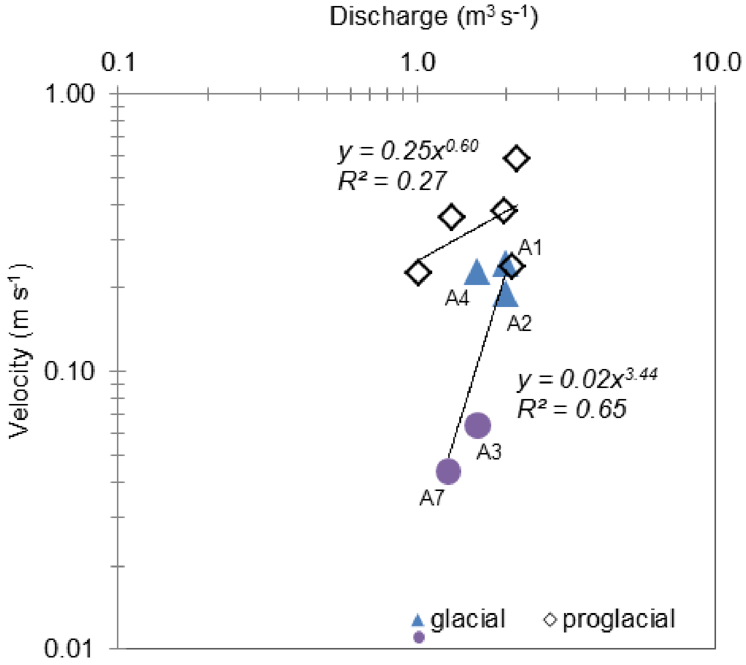

Figure 6. Velocity plotted against discharge for proglacial and glacier-based dye tracer tests conducted during August 2013. Note that the July experiments are not included because there are no contemporaneous measurements of stage from which to calculate discharge. Flow regimes 3 and 4 are illustrated by blue triangles and purple circles respectively.

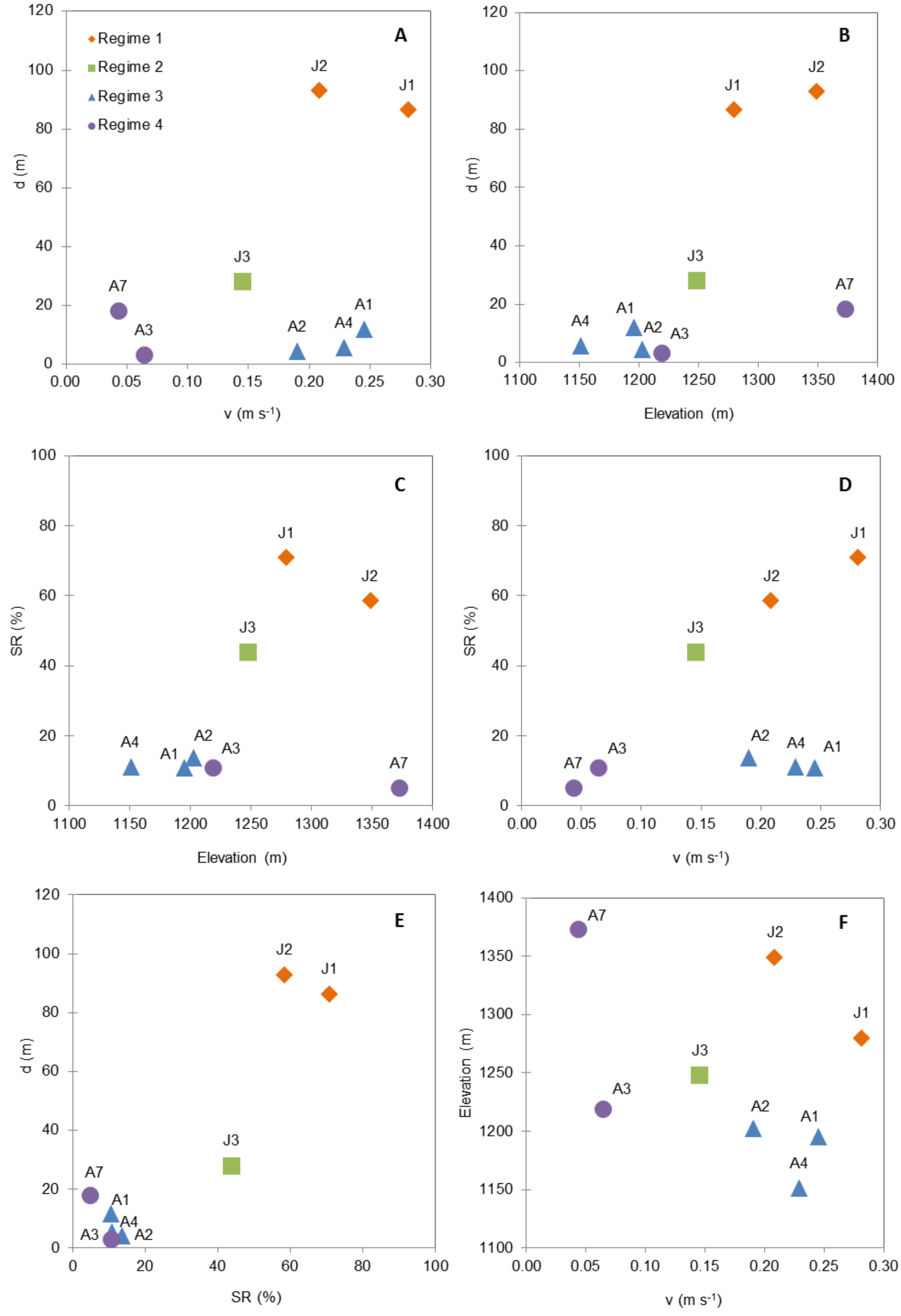

Figure 7. ~~Variation of dispersivity relative to throughflow velocities (A) and elevation (B).~~Plots showing the interaction between the variables: dispersivity (d), throughflow velocity (v), elevation and storage retardation (SR). Meltwater flow regimes 1, 2, 3 and 4 are depicted by orange diamonds, green squares, blue triangles and purple circles respectively.

Flow regime	Elevation	Throughflow velocity	Dispersivity	Storage retardation	Discharge
1	high	high	high	high	n/a
2	moderate	moderate	low	moderate	n/a
3	low	high	low	low	high
4	*not clustered*	low	low	low	low

Figure 8. Characteristics of meltwater flow regimes 1 to 4, where high, moderate and low are relative to measured values. Variables for which values did not fall within the same classification are indicated as "not clustered".

~~**Figure 8.** Surface structure of Rabots glaciär as seen from aerial photography taken on 9th August, 2013. Blue dashed lines represent the boundaries between major flow units (photo credit: Per Holmlund).~~