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Establishing the potential influence of beaver activity on the functioning of rivers and streams and water resource management in Scotland

Appendices

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Josie Geris, Katya Dimitrova-Petrova, Mark Wilkinson

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Appendix 1: Literature search terms

Table A1. Terms used in the literature search in Google scholar and Web of Science to build the evidence base for this report.

Metrics group	Search terms
Geomorphology	total dissolved solids suspended sediment total suspended solids sedimentation rate sediment accumulation sediment deposit channel sinuosity sinuosity channel geomorphology lateral connectivity lateral flow wetland creation
Water quantity	water quantity discharge peak discharge runoff flood water storage water retention groundwater recharge hyporheic zone hydromorphological alteration
Water quality	water chemistry phosphorus phosphate nitrogen nitrite nitrate ammonium carbon total organic carbon dissolved organic carbon organic matter DOC

Appendix 2: Evidence table (literature review)

A2.1. Evidence table database is available upon request. The database shows an overview of the information captured of each study presenting quantifiable evidence (see full reference list in A2.2.), on effect of beaver activity, on one of the 3 groups of metrics. Key aspects of each study, as well as an indicator of which metric is provided by the study, are recorded using a code (provided within the database). Please note that some studies may provide quantifiable information on more than one metric.

A2.2. Reference list – Evidence table

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Appendix 3: Distribution of selected aspects for individual metrics

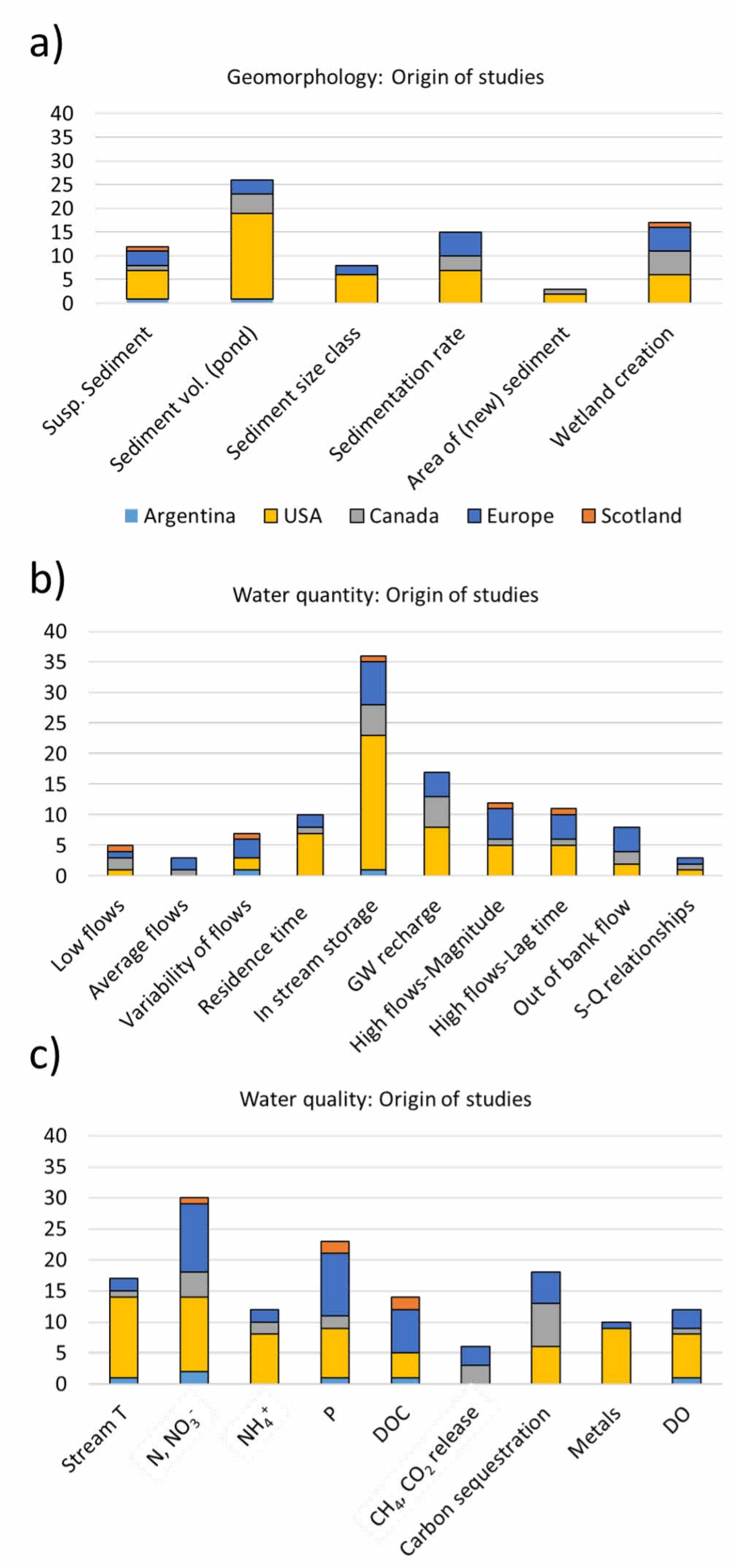

Figure A3.1. Distribution of aspect origin of studies for individual metrics. a) Geomorphology metrics, b) Water quantity, c) Water quality.

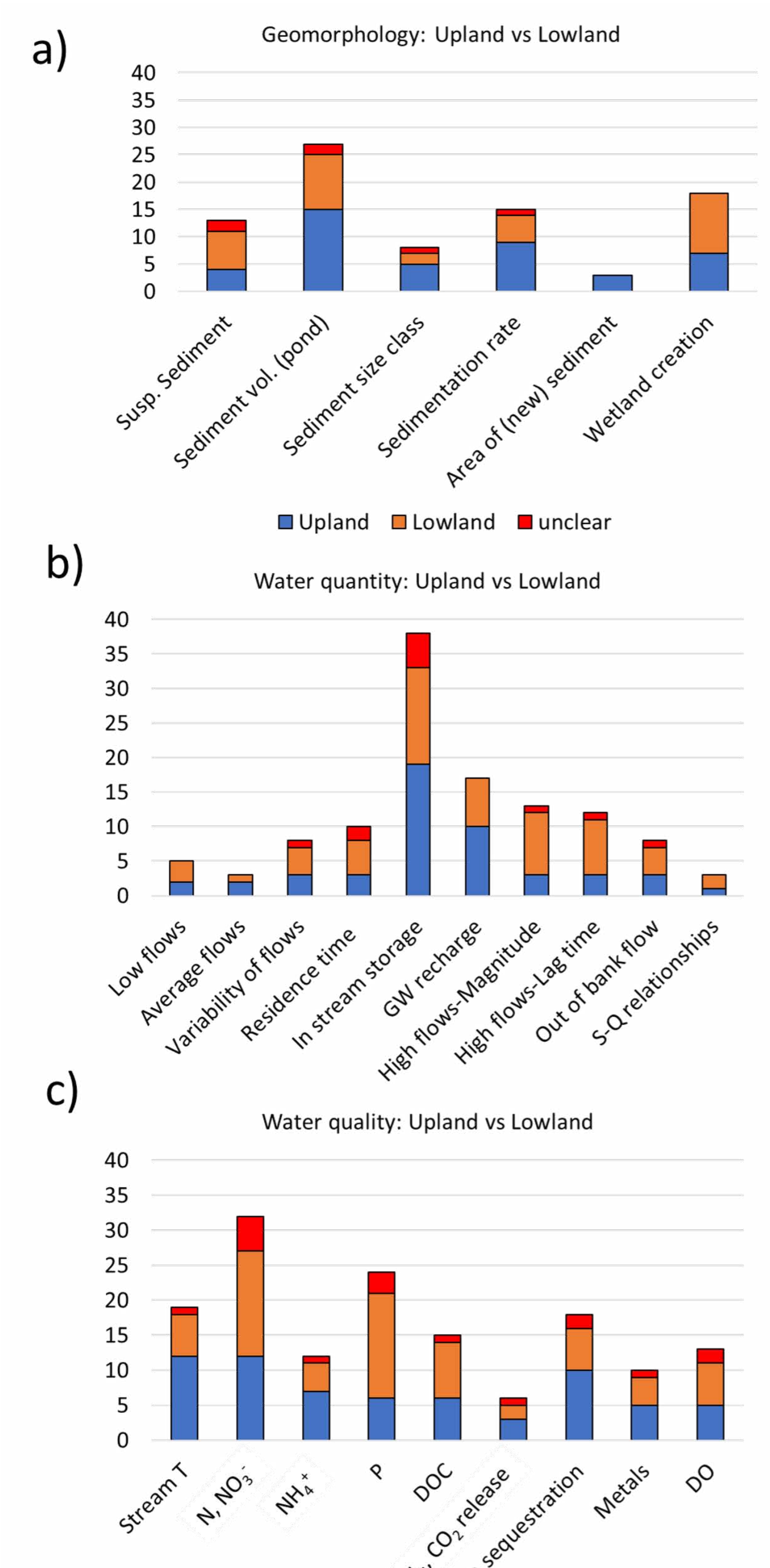

Figure A3.2. Distribution of aspect upland or lowland for individual metrics. a) Geomorphology metrics, b) Water quantity, c) Water quality.

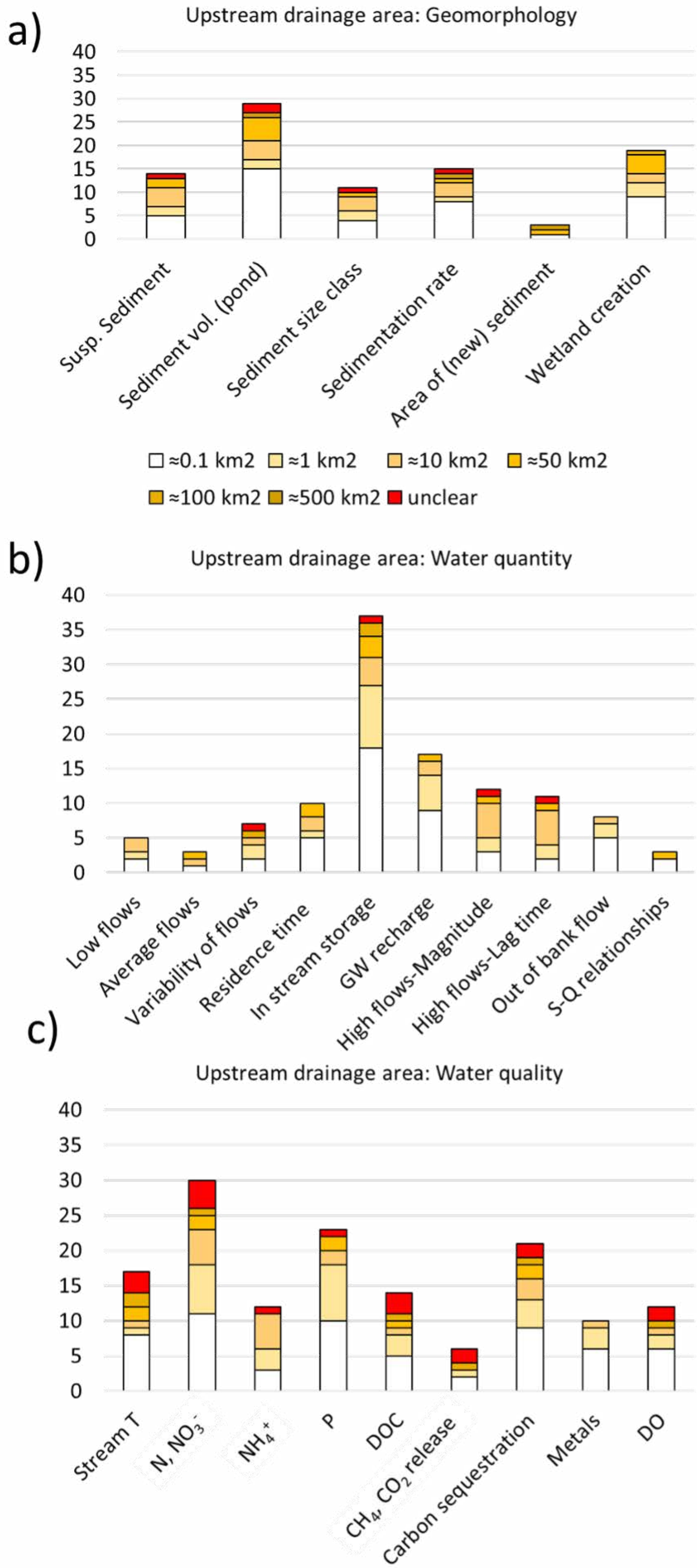

Figure A3.3. Distribution of aspect upstream drainage area for individual metrics. a) Geomorphology metrics, b) Water quantity, c) Water quality.

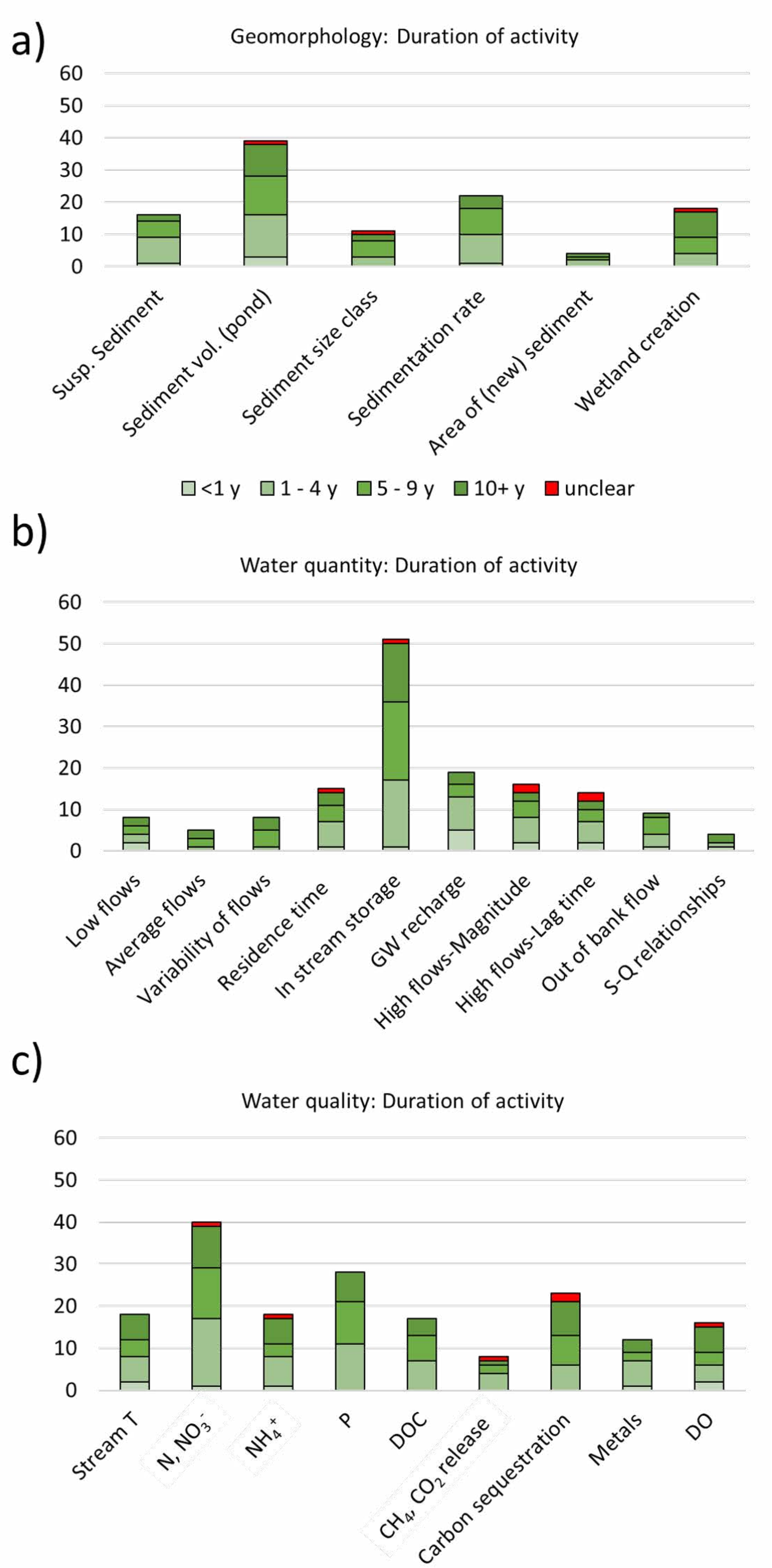

Figure A3.4. Distribution of aspect Duration of activity for individual metrics. a) Geomorphology metrics, b) Water quantity, c) Water quality.

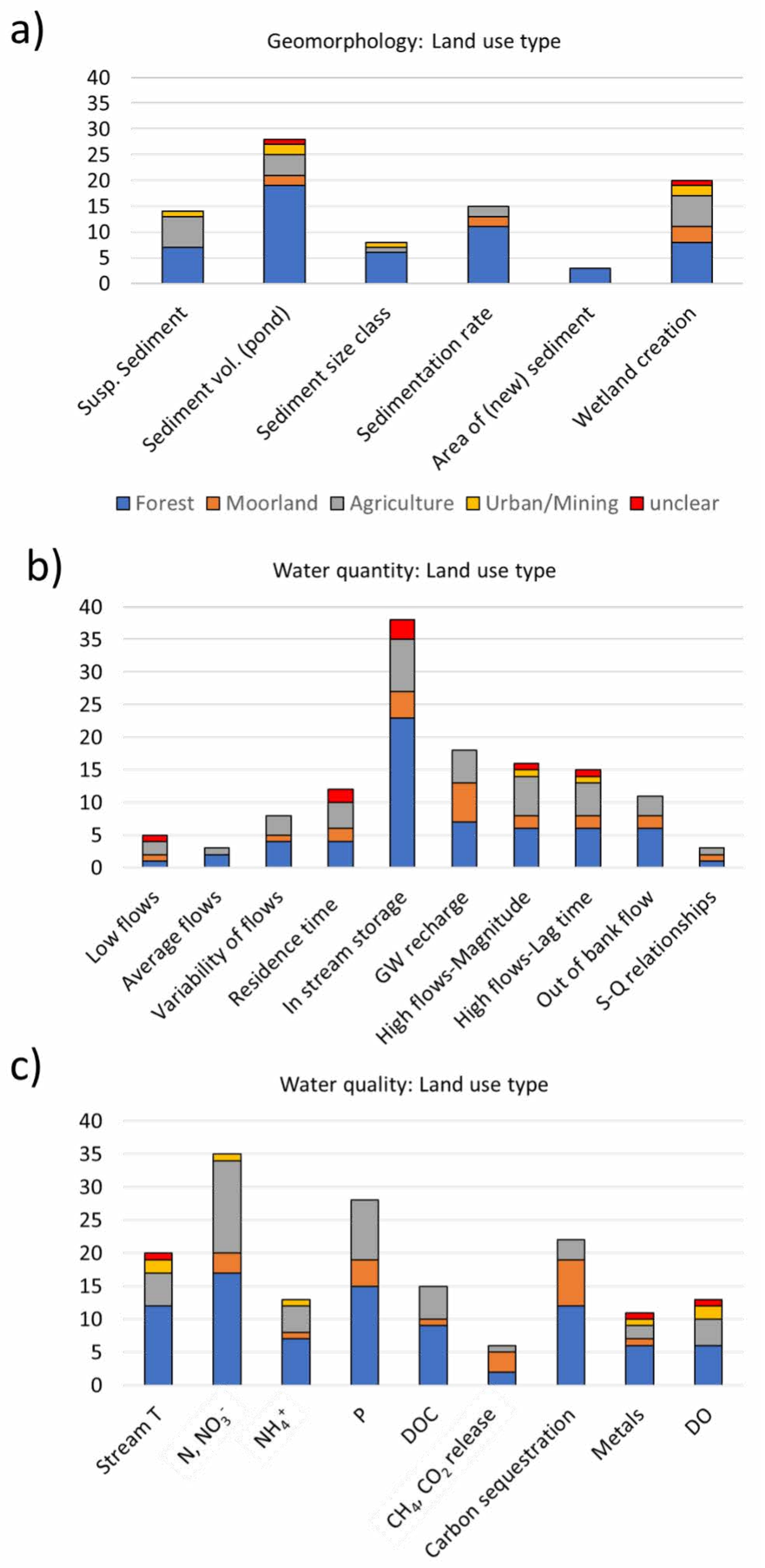

Figure A3.5. Distribution of aspect Land use type for individual metrics. a) Geomorphology metrics, b) Water quantity, c) Water quality.

Appendix 4: Overview of the effects of beaver activity on geomorphology, water quantity, water quality in Scotland

This section provides a short overview of the knowledge collected in Scotland on the effects of beaver activity on physical processes. Table A4.1 provides a summary of the key effects, site-specifications and monitoring. This information is also included in relevant results sections within the main report.

To date, there are three beaver populations in Scotland: Knapdale, Tayside and Beauly (Table A4.1). In Knapdale, Argyll, the reintroduction has been carefully managed and scientifically monitored (Willby *et al.,* 2014). There, a small number of families thrives in a coniferous woodland, in several lochs. In Beauly, Highlands, a small population of beavers is dispersing along the River Beauly and the River Glass. This population is subject to early monitoring, that is mostly not yet available. Tree and Mayo (*Pers. Communication*) provided an estimated three times multiplication of the wetted area in the beaver activity area between 2020 and 2021 (Figure A4.1). ayside hosts the largest beaver population in Scotland, which has been monitored. Tayside is known for its prime agricultural land and popular game fishing area (River Tay) (Gaywood *et al.,* 2015; Coz and Young 2020). The effects of reintroduced beavers in Scotland on ecology and biodiversity have been reported elsewhere (Willby *et al.,* 2014; Gaywood *et al.,* 2015; Campbell-Palmer *et al.,* 2018).

In the Scottish beaver trial in Knapdale, beavers have mainly dammed the outlets of lochs. The damming has increased water levels in some of the lochs. For instance, Dubh Loch experienced a marked and sustained water level rise due to dam building (increase of 1 m and inundating additional 1.41 ha). In terms of water quality, some changes in phosphorus, and increase in DOC, have been observed, but evidence is insufficient to conclude it is due to the beaver activity.

At Tayside, the effect of beaver dam sequences on hydrology and geomorphology has been studied by Law *et al.,* (2016) at the ~0.1 km^2 scale and ongoing work by van Biervliet *et al.,* includes both monitoring and modelling at the ~1 km^2 scale. Both studies involve the same site in the vicinity of Blairgowrie, Perthshire. Law *et al.,* (2016) reported a decrease in high flows magnitude and increase in lag time, while the streamflow data, presented in the study, shows that low flows are sustained higher than at a reference site. In terms of water quality, a reduction of 43% in nitrates and of 49% of phosphorus was measured downstream of a sequence of beaver dams. Colour, used as proxy for DOC, increased by 50% downstream of the beaver dam sequence. Additionally, suspended solids increased by 5.8 times. This was attributed to the fact that the landscape was heavily degraded. The study by Law *et al.,* (2016) also showed that only after 9 years of beaver activity, part of the agricultural land was transformed into a species-rich wetland. In the ongoing study by van Biervliet *et al.,* (In Prep.), preliminary analyses of streamflow data suggest that beaver dams affect discharges across most of the stream hydrograph, notably increasing the lowest 2% of flows. Additionally, beaver pond water levels at the site are remarkably stable between the lowest 5% and highest 10% of stream flows, showing the potential of sustained in-stream storage due to beaver dam building. The increase of low flows and storage due to beaver activity are deemed desirable effects, given the potential impacts of the anticipated climate change projections for longer and drier summers in agricultural Scotland (Kirkpatrick *et al.,* 2021).

Table A4.1. Summary of the knowledge concerning quantifiable evidence on the effects of beavers on hydrology and geomorphology (information extracted from: van Biervliet et al.; Willby et al., 2014; Gaywood et al., 2015; Law et al., 2016; Coz and Young 2020, and on Scottish river types, from Perfect et al., 2013).

Site	Knapdale, Argyll,- Scottish Beaver Trial	Tayside, Perthshire	Beauly/Strathglass, Inverness
Land use	Coniferous woodland	Agriculture and forestry	Woodland, variety of land uses
Landscape characteristics & monitoring	Multiple lochs Semi-natural area Scientific monitoring since reintroduction	Tay, Earn and Forth catchments Productive agriculture and forestry Of interest for fishing Late monitoring	River Glass and River Beauly Semi-natural area Of interest for fishing No monitoring
Socioeconomic context	Mostly single ownership	Multiple landowners Area of high economic interest, potential conflicts with landowners	Multiple landowners Area of touristic interest, potential conflicts with landowners
Upstream drainage area studied	0.1 km² scale (0.04 km²-0.33 km², 16 sites)	0.1 km² and 1 km² scale (0.13 km² and 2.2 km²)	No info
Beavers since	Since 2009	Since 2002-2005	No info
Quantifiable evidence	Willby et al., (2014)	van Biervliet et al.,, In prep.; Law et al., (2016)	Angus Tree and Carmen Mayo, NtaureScot, Personal Communication, 2021
Key findings	At 0.1 km² scale Increased and sustained water levels in some lochs Minor changes in DOC and Phosphorus, but insufficient evidence to attribute to beaver activity	At 0.1 km² scale Attenuation of high flows Decrease of 43% in nitrogen downstream Decrease of 49% in P downstream Increase in DOC of 50% downstream Increase in suspended sediments of 5.8 times Wetland with high biodiversity created and maintained by the beavers At 1 km² scale Beaver dams impact discharges across most of the stream hydrograph, notably including increasing the lowest 2% of flows. Beaver pond water levels at the site are remarkably stable between the lowest 5% and highest 10% of stream flows	Increase in wetted area from 589 m² in 2020 to an estimated 1,558 m² in 2021 (see Figure A4.1)
Suggestions for monitoring		Water temperatures: pond, upstream and downstream (relevant for salmonids) Effects on local geomorphology Greenhouse gas sequestration and release (relevant to payment for ecosystem services) Continue and expand streamflow monitoring Soil moisture and near-surface water storage (relevant to crop growth and storage-discharge relationships) Changes in lateral and longitudinal connectivity (important for fish passage)	Water temperatures: pond, upstream and downstream Greenhouse gas sequestration and release Effects on local geomorphology Streamflow monitoring Water quality monitoring (DO, DOC, nutrients, suspended sediment) Changes in lateral and longitudinal connectivity (important for fish passage)
Water management challenges in the type of stream		Flooding Embankments Riverbank erosion Sediment pollution	Sediment pollution (result of muir burning track construction and wind farm development in peat dominated catchments) Peat conservation Channel narrowing and incision (due to channel engineering, dredging and realignment often carried out further downstream)

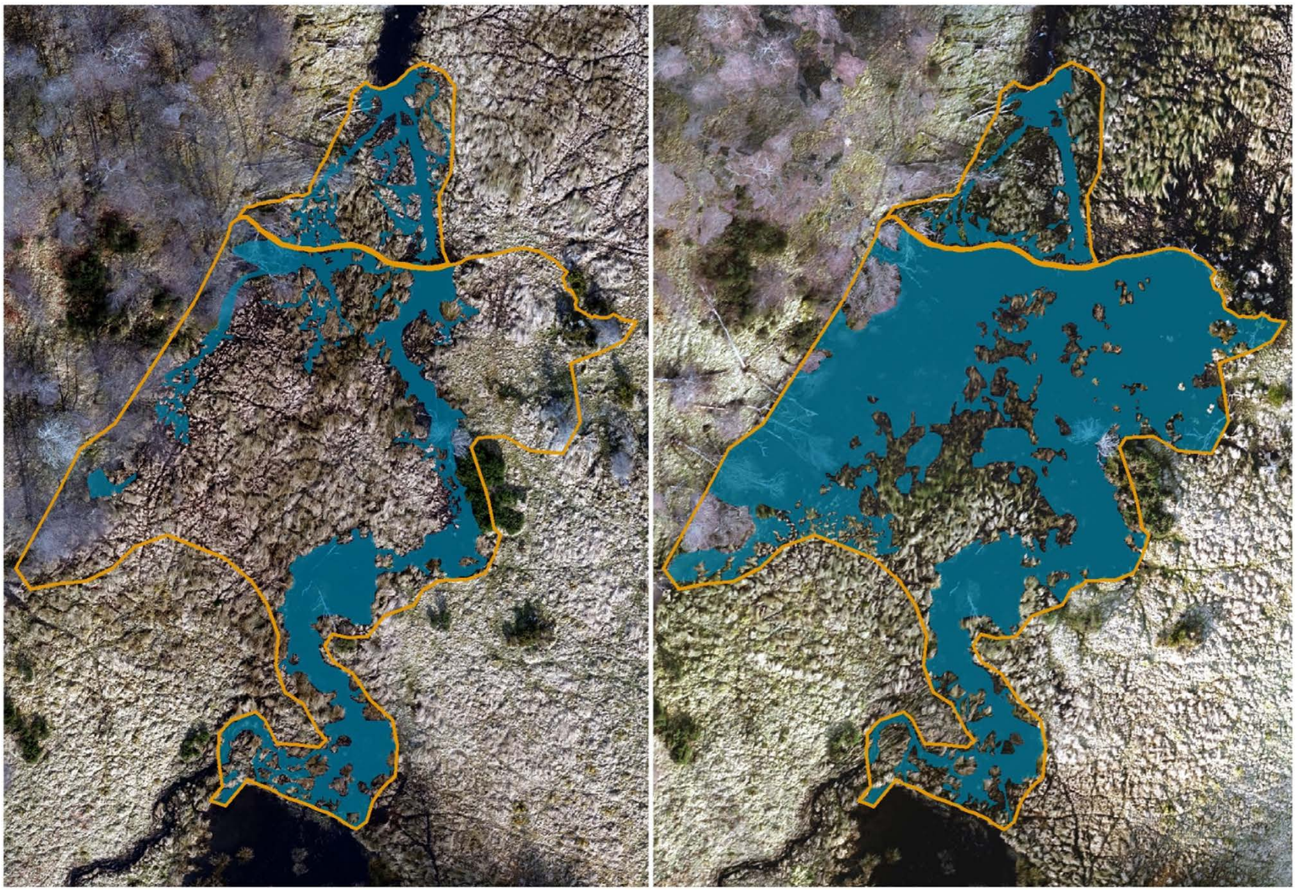

Figure A4.1. Beaver activity-initiated change in surface water area (blue shading) at a site in Scotland (scale 1:750, © NatureScot). The wetted area highlighted in the left-hand diagram was estimated to be 589 m2 in 2020; that in the right-hand diagram was estimated to be 1,558 m2 in 2021. The change is attributed to the enlargement of a dam - one of several on the same headwater stream - resulting in the growth of the beaver pond retained by it.

Appendix 5: Establishing levels of confidence in trend

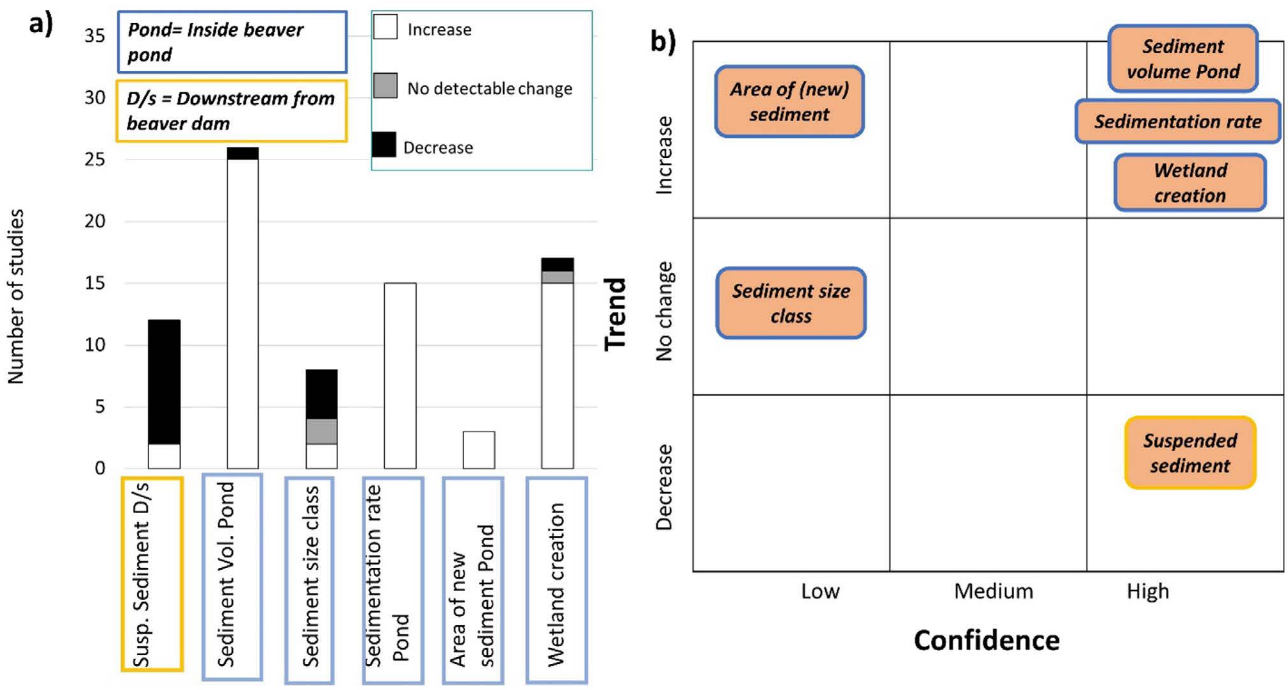

Figure A5.1. Overview of trends in change in geomorphology metrics due to beaver activity. Panel a) Number of studies reporting quantifiable change in water quantity metrics, colour coded by trend; Panel b) Metrics grouped by trend of change and level of confidence.

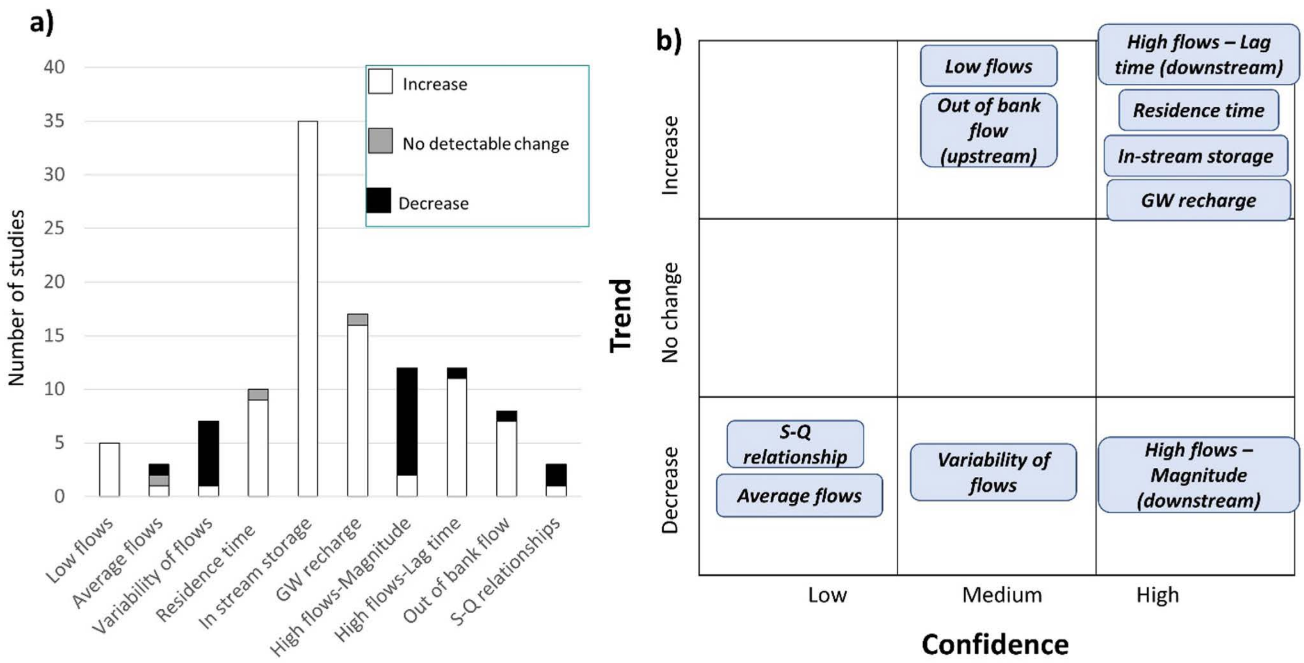

Figure A5.2. Overview of trends in change in water quantity metrics due to beaver activity. Panel a) Number of studies reporting quantifiable change in water quantity metrics, colour coded by trend; Panel b) Metrics grouped by trend of change and level of confidence.

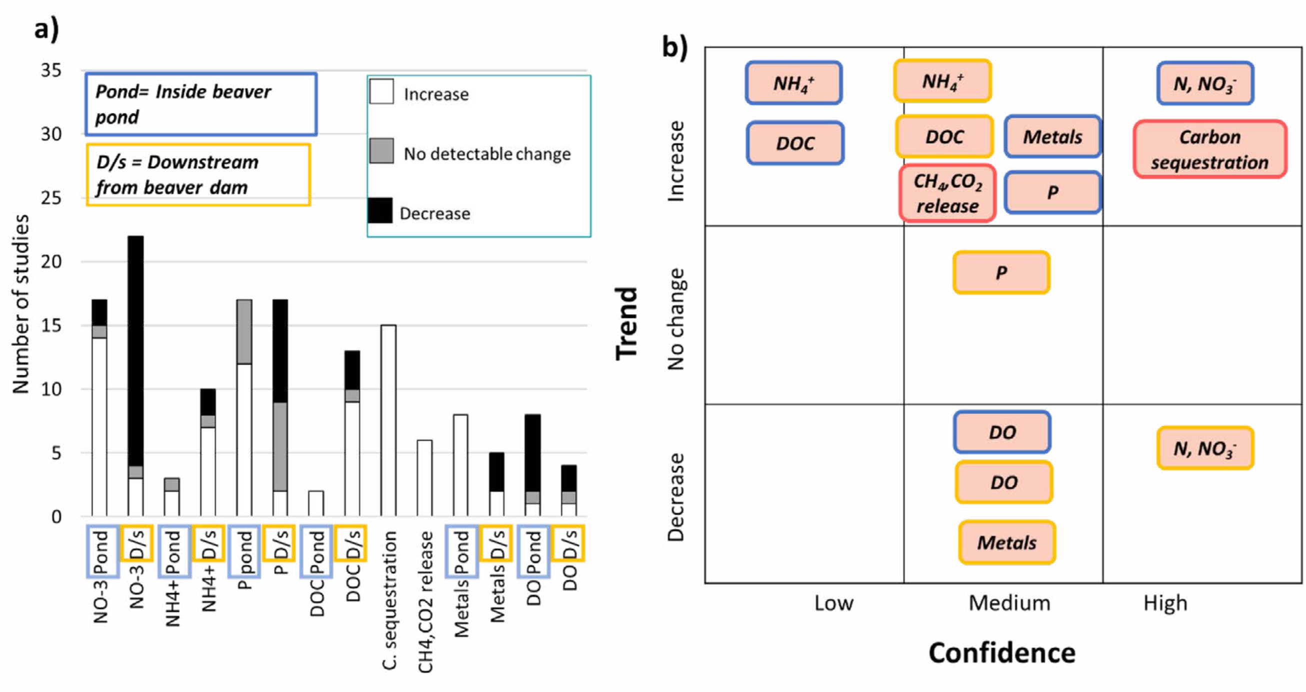

Figure A5.3. Overview of trends in change in water quality metrics due to beaver activity. Panel a) Number of studies reporting quantifiable change in water quantity metrics, colour coded by trend; Panel b) Metrics grouped by trend of change and level of confidence.

Appendix 6: CREW Scottish Beaver Workshop

CREW Scottish Beaver Workshop held on 16 June 2021, 1-4pm BST.

We held a 3-hour virtual workshop to explore the project's preliminarily findings and discuss knowledge gaps on the effect of beavers on relevant physical processes and ecosystem services. We invited experts from a range of organisations (several universities, project research team and steering group including: NatureScot and Scottish Water) and expertise backgrounds (hydrologists, ecologists, geomorphologists).

The workshop had three main sessions. First, the preliminary findings of the project were presented, emphasising the approach of evaluating ecosystem services provided by beaver activity (via quantifiable metrics) as well as evaluating the level of confidence of the existing evidence, in terms of trend and magnitude. This session was followed by two discussion blocks: the first one on Beaver impacts in relation to (ecosystem services in) the Scottish context, and the second one on addressing knowledge gaps and specifically with beaver dam analogues and modelling. Each block of these discussion blocks started with a presentation by an invited speaker, followed by group discussion using interactive, real-time voting (Mentimeter®) and sub-group discussions (breakout rooms). The two discussion blocks were followed by a final brief plenary discussion.

Below we highlight some of the main points of the discussions, followed by the workshop agenda and a list of attendees.

Comments following the research presentation

- Dam structure (i.e., how leaky) and maturity (i.e., how maintained) are thought to be key factors in affecting physical processes related to water quantity, quality and geomorphology. It is difficult to infer this directly from individual studies in the literature. Instead, we tried to address this as much as possible by using proxies of these factors instead (e.g., structure age).
- Typically, in beaver dam systems, there might be one or two key dams, which exert the major impact on hydrological and geomorphological processes. This could affect the results of the studies reported.
- Most studies evaluate upstream versus downstream data to evaluate beaver activity impacts on e.g., hydrology. A suggestion was that this should be complemented more with analyses of control sites.

Discussion session on beaver impacts in relation to ecosystem services in the Scottish context

The first block started with a presentation by Dr Mark Wilkinson. He presented the Scottish context, its pressing water related issues and relevant ecosystem services and emphasised that the focus of the project and analyses and workshop discussion blocks had to be relevant to these. Through the group discussion, the most relevant issues and knowledge gaps for beaver impacts in relation to ecosystem services were identified.

Main themes in discussion

- Better understanding of the effect of beaver activity along the full range of stream discharge relationships, including the associated uncertainties, is needed. Additionally, more precision in measurements and long-term monitoring are key to improve understanding.
- The effect of beaver activity in moorland environments, important in Scotland, is less well understood, given the bias in the literature towards in-stream beavers.
- Maintaining ecological flows, flood risk management and increase/secure water supply at scales up to 10 km^2 were rated by experts as among the most relevant ecosystem services provided/maintained by beaver activity, but also those least well understood. In addition to the impact of beaver activity on physical processes, more research/investigation is needed on the socioeconomical aspects and the cost-benefit trade-off for different groups of society. For example, the well-known effect of local water table rise related to beaver dam building may not be a desirable outcome for every landowner.
- In intense agricultural environments (as e.g., in England or NE, E Scotland) beaver activity can create and maintain the river corridor buffer zones, which present multiple benefits in terms of water quantity regulation and water quality improvement.
- Planning and management of beavers needs to be informed by report/work like the present, in order to assess whether pushing relocation to a certain environment is desirable and beaver activity can be used as a tool in river restoration/ecosystem services restoration.

Discussion session on addressing knowledge gaps with beaver dam analogues and modelling

This second discussion block started with a presentation by Prof. Cherie Westbrook on the similarities and differences between beaver dams and beaver dam analogues, in terms of functionalities and provision of ecosystem services. The group discussion helped elucidate the role of beaver dam analogues and modelling in addressing key knowledge gaps.

Main themes in discussion

- Beaver dam analogues (BDAs) do not fully mimic the functioning of beaver dams and therefore cannot provide the full range of ecosystem services provided by beaver activity according to experts.
- BDAs appear to be more useful for providing ecosystem services in very degraded environments which cannot support beavers. There is high cost of maintenance associated with BDA structures.
- The amount of knowledge/evidence on BDAs is typically less than on beaver activity; because of this and the fact they do not fully mimic beaver activity, it was considered not possible to use knowledge of BDA impacts to address knowledge gaps on beaver activity impacts.
- BDAs were rated somewhat useful for addressing lateral connectivity and wetland creation, regulating flow and regulating out of bank flooding. They were considered much less effective in terms of carbon sequestration, regulating stream temperature and nutrient cycling.
- Modelling the effect of beavers on physical processes (e.g., storage-discharge relationships) using conceptual models is challenging/complex and data-driven approaches are the most informative. In that sense, long-term monitoring is important, in order to be able to calibrate and validate the models.
- Hydraulic modelling of beaver dam functioning is challenging as it requires a 3-D approach, and to mimic effectively the functioning of a beaver dam in the field, sophisticated engineering knowledge is needed.
- Modelling habitat probability is useful in order to understand where beaver might be able to establish within a landscape.
- Modelling was rated by the expert group as somewhat useful for widening boundaries of knowledge (e.g., in different land use or climate scenarios) and upscaling knowledge on effect of beaver activity but much less for other purposes.
- Overall, scaling the impacts of beaver activity is still the most fundamental question that needs to be addressed. At what scale can beavers be considered relevant and when not?

AGENDA

13.00-13.20 Welcome and Introductions (Josie Geris and Martin Gaywood)

13.20-13.55 Research Presentation (Katya Dimitrova-Petrova and Josie Geris)

13.55-14.05 Screen Break

14.05-14.50 Discussion Block 1: Effects of beaver activity in the Scottish context

- Introduction by Dr. Mark Wilkinson

- Identification of knowledge gaps

- Ecosystem Services

14.50-15.00 Screen Break

15.00-15.45 Discussion Block 2: Addressing gaps with beaver dam analogues & modelling

- Introduction Presentation by Prof Cherie Westbrook

- Value of beaver dam analogues

- Value of modelling

15.45-16.00 Wrap up discussions and closing

Attendees

- Stephen Addy, The James Hutton Institute, Aberdeen

- Sophie Beier, CREW (Scotland's Centre of Expertise for Waters)

- Doreen Bell, Scottish Water

- Richard Brazier, University of Exeter

- Lauren Dixon, Scottish Water

- Katya Dimitrova Petrova, University of Aberdeen

- Martin Gaywood, NatureScot

- Josie Geris, University of Aberdeen

- Angela Gurnell, Queen Mary University of London

- Annegret Larsen, University of Wageningen

- Joshua Larsen, University of Birmingham

- Alan Law, University of Stirling

- Alan Puttock, University of Exeter

- Angus Tree, NatureScot

- Cherie Westbrook, University of Saskatchewan

- Mark Wilkinson, The James Hutton Institute, Aberdeen

Appendix 7: Magnitude of change for selected metrics

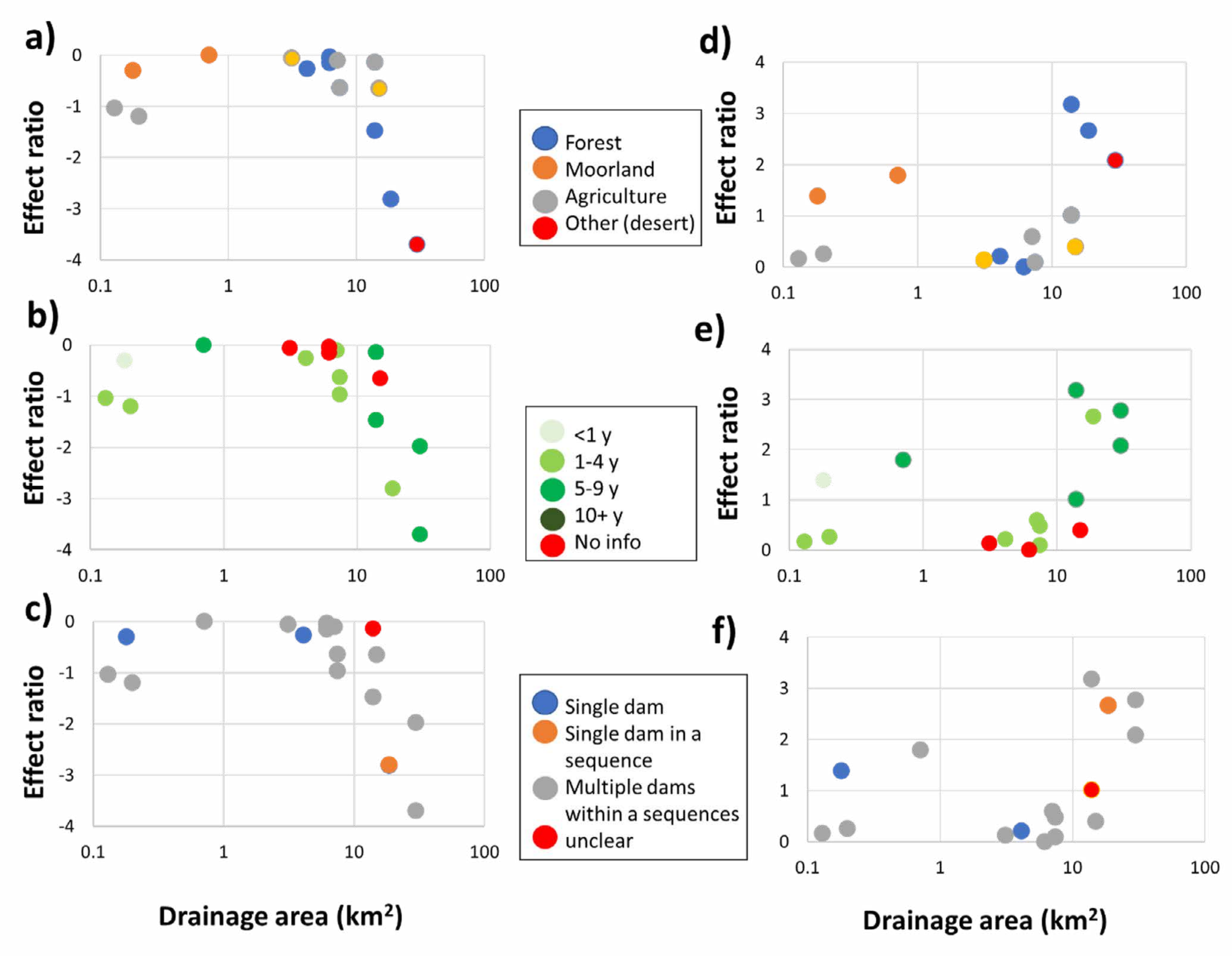

Figure A7.1. Effect ratios of change in magnitude and lag time of high flows with increasing spatial scale. Decrease in high flows magnitude in environments with different land use types a) with duration of activity b) and extent of activity c) Increase in high flows lag time in different environment types d), with duration of activity e) and extent of activity f).

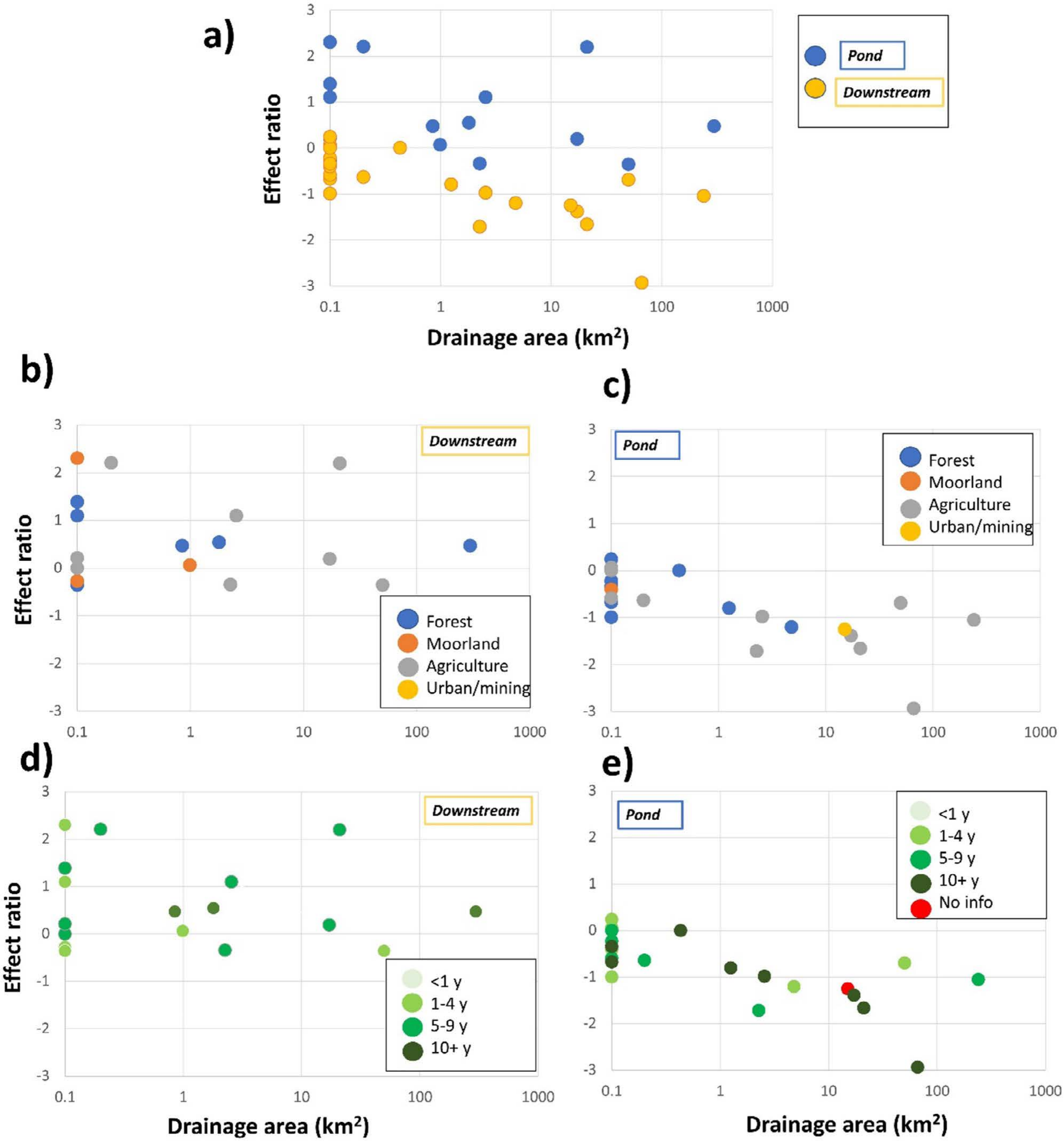

Figure A7.2. Effect ratio of change inside pond and downstream from pond due to beaver activity. a) Overview of effect ratios for N, NO3- b) and d) Effect ratio downstream depending on environment type and age of activity respectively; c) and e) Effect ratio inside the pond depending on environment type and duration of activity respectively.

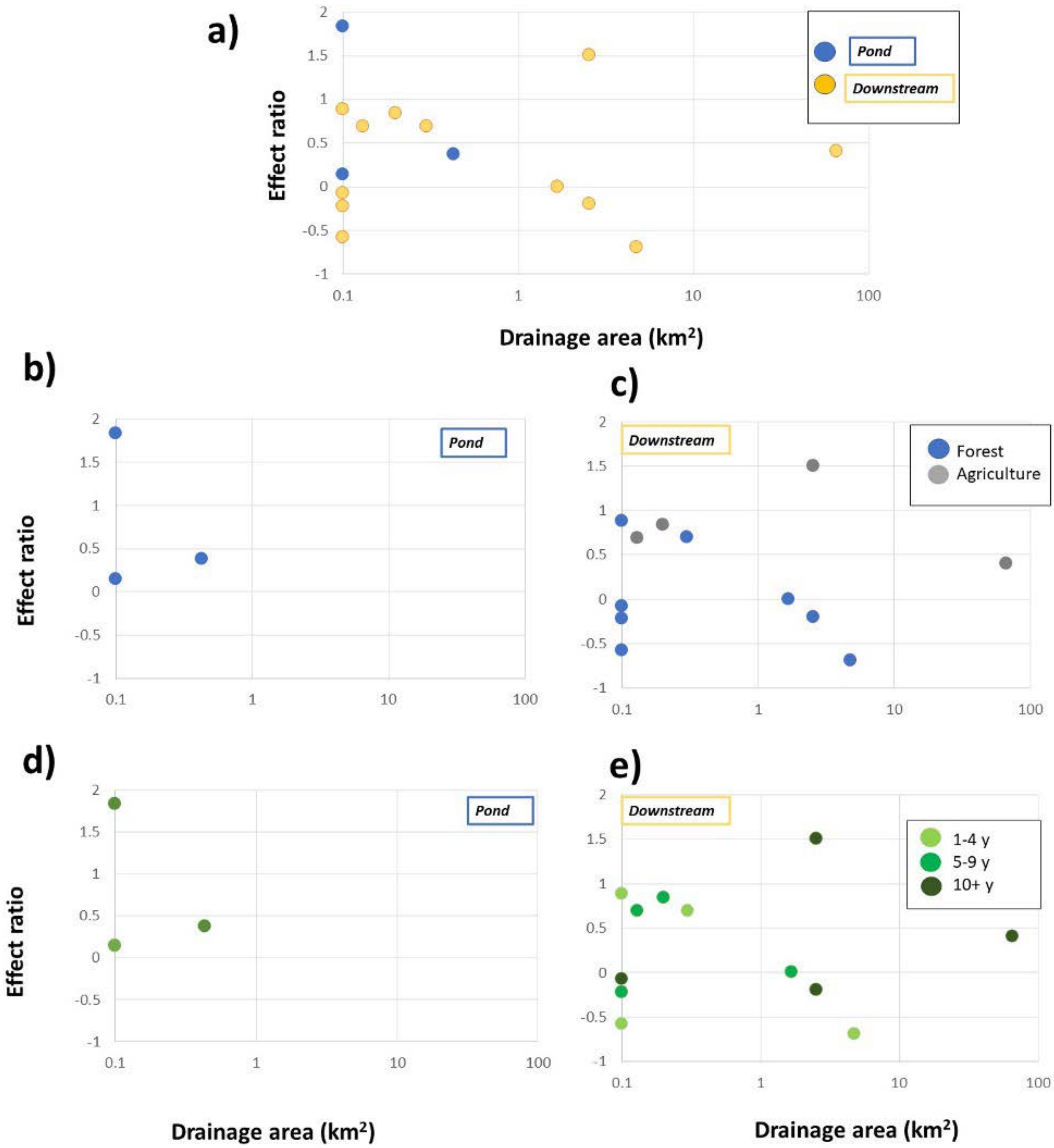

Figure A7.3. Effect ratio of change inside pond and downstream from pond due to beaver activity. a) Overview of effect ratios for DOC, b) and d) Effect ratio downstream depending on environment type and age of activity respectively; c) and e) Effect ratio inside the pond depending on environment type and duration of activity respectively.

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