Universitat de Girona

TOWARDS BENEFIT ORIENTED REHABILITATION TO MAKE DEGRADED LAKES MORE RESILIENT TO EXTREME CLIMATIC EVENTS

Margaret Rosé Armstrong

DOCTORAL THESIS

Towards benefit oriented rehabilitation to make degraded lakes more resilient to extreme climatic events

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2024

DOCTORAL PROGRAMME IN WATER SCIENCE AND TECHNOLOGY

Supervised by:
Dr. Vicenç Acuña Salazar **Dr. Lisette de Senerpont Domis**

Presented to obtain the degree of PhD at the University of Girona

Dr Vicenç Acuña Salazar, of the Resources and Ecosystems Research Area of the Catalan Institute for Water Research, and Prof. Dr Lisette de Senerpont Domis of the Department of Aquatic Ecology at the Netherlands Institute of Ecology,

DECLARE:

That the thesis titled *Towards benefit oriented rehabilitation to make degraded lakes more resilient to extreme climatic events*, presented by Dr Margaret Armstrong to obtain a doctoral degree, has been completed under our supervision.

For all intents and purposes, we hereby sign this document.

Dr Vicenç Acuña Salazar   Prof. Dr Lisette de Senerpont Domis

Girona, August 2023

Acknowledgments

I could go for pages about all of the memorable experiences that happened over my years at the ICRA, NIOO, WUR and W+B and how glad I am to have taken part in them. Many people have helped make these past few years remarkable. I am grateful to everyone at the Catalan Institute for Water Research for their hospitality and collaboration. In particular, I would like to thank you **Vicenç** for your guidance and encouragement throughout the PhD process. Your reminders about taking the reins were invaluable with cultivating confidence and with moving the projects forward. Even if COVID cut my secondment short, the time I spent in Girona helped shape my professional view immensely. **Rafa**, I am grateful I got to chat with you during coffee breaks at ICRA to talk about work and Girona. I also appreciate your help with easing into the institute and with completing the university requirements. **Elias**, thanks for the talks during breaks and the insight into Girona. It was fun getting to hang out in both Girona and Wageningen!

With being based primarily in the Netherlands, there were also people at the NIOO, WUR and W+B that were very helpful throughout the PhD. **Lisette**, thank you for the chance to grow, learn and enjoy this once-in-a-lifetime opportunity with the PhD. Your support has been invaluable in discovering how I can contribute to science and associated professional fields and I hope to do this justice with my future career. **Mike**, thank you for all of the memorable conversations, science-related or otherwise, throughout the PhD. It was so much fun getting to work on projects and through the MANTEL program with your steadfast guidance and help.

To the **NIOO AqE** community, thank you for the many years spent learning and laughing together. To the PhDs especially, being able to grow through this process together made a joy out of an intense experience.

Thanks to the WUR **Aquatic Ecology and Water Quality Group** for the chance to take part in the Thursday lunch meetings and holiday celebrations. The chance to be part of this group helped with not only my professional growth, but also with becoming more integrated into the Wageningen community.

Additionally, I had the opportunity to spend time with the consultants at **Witteveen+Bos**. I am grateful for the opportunity to collaborate on projects and to observe the consulting sector.

To the **MANTEL** community – ESRs and supervisors alike – thank you for the welcoming community. The chance to work alongside and learn from all of you has made this PhD a remarkable experience on numerous fronts. The memories and lessons will stay with me as I move forward into a career.

Many people outside of academia provided unwavering support as I went through this process. Thank you to all of my family and friends for your advice, encouragement and interest in my work.

The author of this thesis was financially supported by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska Curie grant agreement number 722518 and by the Royal Dutch Academy of Sciences (KNAW).

All photographs in this thesis were taken by the author.

List of publications

Publications derived from the PhD thesis published in journals:

- **Armstrong, M.,** Zhan, Q., Munthali, E., Jin, H., Teurlincx, S., Peters, P., Lürling, M., and de Senerpont Domis, L.N. (2023) Stressors in a bottle: a microcosm study on phytoplankton assemblage response to extreme precipitation events under climate warming, DOI: 10.1111/fwb.14109

- **Armstrong, M.,** Aksu Bahçeci, H., van Donk, E., Dubey, A., Frenken, T., Gebreyohanes Belay, B.M., Gsell, A.S., Heuts, T.S., Kramer, L., Lürling, M., Ouboter, M., Seelen, L.M.S., Teurlincx, S., Vasantha Raman, N., Zhan, Q., and de Senerpont Domis, L.N. (2022) Making waves: Lessons learned from the COVID-19 anthropause in the Netherlands on urban aquatic ecosystem services provisioning and management. Water Research, DOI: 10.1016/j.watres.2022.118934

- **Armstrong, M.**, Kramer, L., de Senerpont Domis, L.N., van Wijk, D., Gsell, A.S., Mooij, W.M., and Teurlincx, S. (2021) Flipping Lakes: Explaining concepts of catchment-scale water management through a serious game. Limnology and Oceanography: Methods, DOI: 10.1002/lom3.10436

- **Armstrong, M.**, Kramer, L., Acuña, V., Antão-Geraldes, A.M., Borre, L., Dieperink, C., Ibelings, B.W., Rusak, J.A., Stelzer, J.A.A., Teurlincx, S., Yokota, K., and de Senerpont Domis, L.N. (2023) Opportunities for improving the role of science in lake management: Lessons from North America and Europe. In preparation for submission.

List of abbreviations

COVID-19: Coronavirus

CWA: Canada Water Act

DPSIR: Drivers-Pressures-States-Impacts-Responses (framework)

ECE: Extreme climatic event(s)

EU: Europe

GDPR: General Data Protection Regulation (European Union)

GLEON: Global Lake Ecological Observatory Network

GLEON21: Global Lake Ecological Observatory Network, 21st All-Hands' Meeting

HHSK: Hoogheemraadschap van Schieland en de Krimpenerwaard (regional Dutch water management agency)

IPBES: Intergovernmental Panel on Biodiversity and Ecosystem Services

IPCC: Intergovernmental Panel on Climate Change

LME: Linear mixed-effect (model)

MANTEL: Management of Climatic Extremes in Lakes and Reservoirs for the Protection of Ecosystem Services (European Union Innovative Training Network)

NA: North America

NALMS: North American Lake Management Society

NIOO: Netherlands Institute of Ecology

NIOO-KNAW: Netherlands Institute of Ecology (Royal Dutch Academy of Science)

PAR: Photosynthetic active radiation

PRC: Principal response curve (analysis)

RLM: Reservoir and Lake Management working group (GLEON)

SMAC: Scientists and Managers Communicating (GLEON)

TMDL: Total maximum daily load

UNESCO: United Nations Educational, Scientific and Cultural Organization

USCWA: United States Clean Water Act

WFD: Water Framework Directive

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Resum

La delimitació de l'època geològica actual com a "Antropocè", derivat del prefix "antro-" que significa "humà", resumeix encertadament la gran magnitud en què els humans han afectat la biosfera. Per a molts ecosistemes, aquestes pressions han provocat degradacions a llarg termini de la seva salut i funcions. Els sistemes d'aigua dolça com els llacs són especialment susceptibles, ja que aquests cossos d'aigua lenítics actuen com a sentinelles del canvi climàtic a la regió acumulant informació de tota la conca aigües amunt. Amb les pressions d'accions antropogèniques i escenaris climàtics que es preveu que continuïn, si no que s'intensificaran, en les properes dècades, hi ha preocupació pel deteriorament dels ecosistemes lacustres.

De les projeccions climàtiques, una de les preocupacions més recents és la intensificació de la freqüència i la gravetat dels esdeveniments climàtics extrems ("ECE"), o un esdeveniment climàtic com una onada de calor o una precipitació que es troba als extrems de la cua (per exemple, el percentil 99) del corba de distribució per a aquesta regió o època de l'any. El potencial d'aquests esdeveniments per instigar interrupcions desproporcionades als sistemes d'aigua dolça a tot el món pot ser important. Juntament amb altres pressions no climàtiques derivades de les accions humanes, com ara el canvi generalitzat d'ús del sòl i els brots pandèmics, hi pot haver múltiples pressions que afectin la biosfera de manera seqüencial o conjunta. Depenent de la naturalesa de la pressió, aquests es poden classificar com a estressors de "pols", que generalment són esdeveniments de curta durada, com ara onades de calor o precipitacions extremes, i estressors de "premsa" que tenen una durada prolongada o crònica, com ara alteracions de l'ecosistema (per exemple, urbanització, construcció de preses, etc.) o canvi climàtic.

La degradació dels sistemes presenta reptes no només per a la pròpia biosfera, sinó també per a les comunitats humanes, ja que els nostres mitjans de vida estan lligats i construïts a partir de les funcions i els valors que proporciona la biosfera. Si es permet que la tendència a augmentar les pressions continuï sense intervenció, la salut humana, el benestar i les economies es podrien veure afectades tant com els habitants de l'ecosistema. Com que els llacs són els sistemes molt utilitzats i vulnerables, per abordar aquests problemes polifacètics caldrà mirar més enllà del sector científic per abordar els reptes presents i futurs.

En aquesta tesi, la investigació rastreja la relació causa-efecte des de 1) l'ocurrència d'esdeveniments extrems fins a 2) les seves implicacions en les funcions dels ecosistemes, fins a 3) l'efecte sobre la prestació de serveis ecosistèmics i 4) les implicacions que podrien tenir les col·laboracions intersectorials en la la rehabilitació dels ecosistemes. Això es duu a terme mitjançant un enfocament interdisciplinari i cada capítol aborda diversos aspectes d'aquesta cadena causa-efecte.

El **primer capítol** va investigar les implicacions dels estressors climàtics individuals i coincidents mitjançant un experiment de microcosmos factorial complet. Pel que fa a la tesi general, aquest capítol es va centrar en la relació causa-efecte dels esdeveniments extrems en el funcionament dels ecosistemes. Les aplicacions d'un esdeveniment d'escalfament (pressió de premsa), un esdeveniment de precipitació (pressió de pols) i una combinació d'ambdós es van mesurar contra les reaccions d'una comunitat de fitoplàncton formada per *Anabaena flos-aquae* (cianobacteri), *Chlorella vulgaris* (alga verda) i *Synedra*. (diatomees). Dins dels microcosmos, el tractament d'escalfament individual va donar lloc a que el resultat esperat del cianobacteri es convertís en l'espècie dominant. L'esdeveniment de precipitació, en canvi, va tenir un efecte transitori de curta durada sobre l'abundància de fitoplàncton. Finalment, el tractament combinat d'un esdeveniment d'escalfament i un esdeveniment de precipitació va produir un efecte global

que va ser menor que l'observat amb els esdeveniments individuals. Aquesta situació d'esdeveniment coincident no va tenir l'efecte additiu, multiplicatiu o sinèrgic que es preveia mitjançant augments significatius de la comunitat de fitoplàncton. El disseny de l'experiment es va basar en les condicions mitjanes d'estiu holandeses, inclosa la composició de la comunitat d'algues i els tractaments climàtics que es van aplicar. Tot i que els resultats posteriors d'aquest experiment no es poden traduir directament en sistemes de llacs similars, el resultat proporciona informació sobre els mecanismes en què els sistemes de llacs experimenten efectes mitigadors quan s'aplicaven pressions coincidents. S'ha plantejat la hipòtesi que la resiliència intrínseca als sistemes complexos és capaç de disminuir l'impacte de les pressions. Amb la tendència d'intensificació dels esdeveniments climàtics extrems en conjunció amb altres pressions, queda la pregunta fins a quin punt els sistemes d'aigua dolça seran capaços de resistir l'atac de les pressions abans que la degradació continuada provoqui un col·lapse de l'ecosistema.

El **capítol segon** va avaluar els impactes que la pandèmia de coronavirus ("COVID-19") ha tingut en les interaccions humanes amb els sistemes de llacs en regions seleccionades altament urbanitzades. Dins de la cadena causa-efecte, aquest capítol es va centrar en l'ocurrència d'un esdeveniment extrem (la pandèmia), el seu efecte sobre les funcions aquàtiques i els impactes posteriors en la prestació de serveis ecosistèmics. Les recomanacions d'accions de gestió que es van formular en aquest capítol també comencen a abordar el quart component de la cadena causa-efecte sobre la correcció. A partir del canvi sobtat i generalitzat en els comportaments humans a causa de les normatives sanitàries, hi va haver diferents canvis en les interaccions que es van produir amb els sistemes aquàtics (tant augmentant com decreixent en funció de les regulacions locals de mobilitat que s'aplicaven). En primer lloc, l'efecte de la pandèmia es podria rastrejar directament al seu efecte sobre l'explotació dels serveis dels ecosistemes aquàtics, tal com es demostra en quatre estudis de cas. Per exemple, el primer estudi sobre la qualitat de l'aigua dels canals a Amsterdam, als Països Baixos, va revelar que la disminució del trànsit de vaixells va donar suport a l'augment de la claredat de l'aigua juntament amb l'establiment de vegetació submergida que va crear una zona d'hàbitat. Els altres tres estudis de cas (ús de l'aigua de bany, pesca recreativa i parcs nacionals) van demostrar situacions d'augment de la demanda de serveis ecosistèmics. Això podria haver estat degut a la pandèmia de COVID-19 que va instigar un moviment cap a la recerca de consol a la natura, sobretot perquè molts altres llocs (per exemple, parcs d'atraccions, viatges de vacances, etc.) no eren accessibles durant els períodes de confinament. En segon lloc, els estudis de cas van il·lustrar el feedback dins d'aquests sistemes de naturalesa humana. Per exemple, amb els canals, les pressions de navegació exercides sobre el sistema es van fer evidents una vegada que la majoria de la navegació motoritzada va cessar al sistema i es va restaurar un altre servei ecosistèmic (hàbitat de les espècies). Els tres estudis de casos d'esbarjo també van il·lustrar com un augment de l'ús humà dels serveis pot provocar disminucions en les funcions dels ecosistemes, especialment si no s'apliquen les millors pràctiques (per exemple, els principis de "no deixar rastre"). Durant aquest període de la COVID-19, hi ha hagut oportunitats perquè la gent es torni a familiaritzar amb els seus sistemes d'aigua locals i recordi el valor que aquests sistemes poden proporcionar. Prendre mesures per mantenir l'alta estima i consideració que més persones estan donant actualment als sistemes naturals en el futur podria ser un punt d'inflexió per establir pràctiques humanes més sostenibles i reduir les pressions que s'exerceixen sobre ells.

El **capítol tres** es basa en el joc seriós "Flipping Lakes" que vaig dissenyar i crear conjuntament amb un company. Pel que fa a la cadena causa-efecte de la tesi, aquest joc rastreja la totalitat de la cadena causa-efecte començant per l'ocurrència de pressions extremes fins a la implementació d'intervencions de gestió. Mitjançant la interacció amb el joc, els jugadors es van comprometre amb els components causa-efecte actuant com a "gestor de conca hidrogràfica" encarregat de preservar l'estat clar dels llacs del joc, mantenint així la capacitat d'aquestes masses d'aigua per proporcionar serveis ecosistèmics. Des d'un punt de vista teòric, aquest joc permet als jugadors veure totes les interaccions causa-efecte a mesura que es desenvolupen, fins i tot quan a la vida real les implicacions es poden produir durant llargs períodes de temps o ser difícils de desxifrar. La personalització del joc per "construeix les teves pròpies conques" permet als jugadors una gran oportunitat per simular un sistema específic, crear una captació fictícia o explorar-ne diverses combinacions. A més, el joc seriós actua com una eina tant per augmentar l'alfabetització ambiental dels jugadors, així com a suport visual per a les discussions intersectorials. El joc es va jugar en nombrosos llocs per avaluar l'eficàcia del seu impacte en l'alfabetització ambiental. Amb els estudiants universitaris, les autoavaluacions dels jugadors van revelar una millor comprensió de conceptes com esdeveniments climàtics extrems, estats estables alternatius i mesures proactives. L'aportació qualitativa de l'administració universitària i dels professionals de la ciència del llac van expressar el seu suport a l'aplicació de jocs seriosos per transmetre coneixement, especialment en aquest format de joc accessible on els conceptes de "jugar a un joc" són relativament universals per a la majoria de la gent. Els ciutadans i les parts interessades dels llacs i de la conca més àmplia poden ser col·laboradors valuosos per recollir coneixement, desenvolupar plans de gestió a mida i implementar intervencions de gestió. L'ús d'eines que facin que els conceptes de ciència i gestió dels llacs estiguin més fàcilment disponibles, així com reduir les barreres a les discussions tècniques, pot conduir a una major implicació de la comunitat. D'aquesta manera, una major implicació i propietat dels plans d'intervenció pot augmentar notablement la seva eficàcia. Amb els reptes que afecten actualment els llacs i les seves conques, pot ser útil treballar activament per incorporar les parts interessades en la presa de decisions i la implementació.

Pel que fa al tema de les col·laboracions intersectorials, el **capítol quatre** va investigar l'abast de la (des)connexió entre els científics i els gestors del llac juntament amb mètodes per unir encara més els sectors. En la cadena causa-efecte de la tesi, aquest capítol es va centrar en les col·laboracions intersectorials per a la gestió dels llacs en el context de les pressions contínues (per exemple, esdeveniments extrems), les funcions de l'ecosistema i la prestació de serveis ecosistèmics. Donat l'abast d'influència que els esdeveniments extrems poden tenir sobre els llacs i, posteriorment, tant sobre la biosfera com les comunitats antròpiques, per poder mitigar o evitar els efectes negatius requerirà un coneixement i una planificació intersectorial. L'enquesta en línia dirigida als gestors dels llacs es va desenvolupar per obtenir la seva perspectiva sobre quins són els principals reptes que afecten la gestió dels llacs, quins són els objectius de la gestió, quins papers juguen la ciència i els científics en la gestió dels llacs i com les col·laboracions es podrien millorar. Les respostes regionals d'Amèrica del Nord i d'Europa van demostrar la superposició i les disparitats entre les respostes acumulades. Per exemple, es van mostrar tendències similars entre les regions pel que fa a quins reptes estan afectant els ecosistemes lacustres (degradació de l'hàbitat i espècies invasores) i quines barreres dificulten les col·laboracions (finançament). Per contra, hi va haver desviacions entre les dues regions, tal com es va demostrar a través de respostes diferents a quin és el paper (s) dels científics en les discussions de gestió en l'actualitat i quines oportunitats futures hi ha per a una participació addicional (els directius nord-americans van veure nombroses oportunitats per implicar científics en l'actualitat i en el futur, els directius europeus contracten científics per a tasques seleccionades amb poca oportunitat percebuda per a una participació addicional). Diferents circumstàncies entre les dues regions (per exemple, lleis i polítiques rectores, valors generals de la societat, diferència del sistema biogeoquímic local, etc.) podrien proporcionar explicacions per a les desviacions. Estudis previs i nombrosos projectes intersectorials han establert diversos mètodes per col·laborar, tot i que cap enfocament únic és adequat per a totes les associacions de gestió ciència. Com a reconeixement de les conclusions de l'enquesta, aquests mètodes s'han d'adaptar a la situació regional en què treballen els directius. La co-creació de marcs de col·laboració i el desenvolupament del coneixement podria avançar cap a l'assoliment dels objectius de gestió dels llacs, especialment en un món extrem. La multitud de pressions que afecten els sistemes de llacs d'aigua dolça ha donat lloc a una tendència global de degradació prolongada i sostinguda. La intensificació de les ECE i la persistència de l'estrès antropogènic són motius de preocupació, sobretot pel grau de degradació prolongat i sostingut que ja hi ha, ja que aquestes pressions extremes presenten reptes que afecten la biosfera i les comunitats humanes. Mantenir els enfocaments d'*statu quo* per utilitzar, estudiar i gestionar els llacs no serà suficient per millorar o preservar la salut i les funcions dels ecosistemes en el futur. Navegar pel límit de la sostenibilitat de les funcions i serveis del llac en un Món governat per ECE requereix mètodes informats, proactius, inclusius i holístics. En reconèixer la urgència de la situació i adaptar els enfocaments utilitzats per a aquesta nova realitat, la biosfera i les comunitats antròpiques dependents poden superar els extrems.

El Resumen

La delineación de la época geológica actual como el "Antropoceno", derivado del prefijo "antro-" que significa "humano", resume acertadamente la gran magnitud en la que los humanos han afectado a la biosfera. Para muchos ecosistemas, estas transformaciones han causado degradaciones a largo plazo en su salud y funciones. Los ecosistemas de agua dulce, como los lagos, son particularmente susceptibles, ya que actúan como centinelas del cambio en la región al acumular información de toda la cuenca hidrográfica. Dado que se proyecta que las presiones antropogénicas y los escenarios de cambio climático continúen, si no se intensifiquen, en las próximas décadas, existe preocupación con respecto al deterioro de los ecosistemas lacustres.

De las proyecciones climáticas, una de las preocupaciones más recientes es la frecuencia y gravedad de los eventos climáticos extremos ("ECEs" de sus siglas en ingles), como olas de calor o precipitaciones que se encuentran en los extremos de la curva de distribución (por ejemplo, el percentil 99) para esa región o época del año. El potencial de estos eventos para provocar alteraciones desproporcionadas en los ecosistemas de agua dulce a nivel global puede ser significativo. Combinado con otras presiones no climáticas derivadas de las acciones humanas, como el cambio generalizado del uso de la tierra y brotes de pandemias, pueden existir múltiples presiones que afecten a la biosfera de forma secuencial o simultánea. Dependiendo de la naturaleza de la presión, estos factores pueden clasificarse como estresores "puntuales" que generalmente son eventos de corta duración, como olas de calor o precipitaciones extremas, y estresores "continuos" que tienen una duración prolongada o crónica, tales como alteraciones del ecosistema (por ejemplo, urbanización, construcción de represas, etc.) o el cambio climático.

La degradación de los ecosistemas presenta desafíos no solo para la biosfera, sino también para las comunidades humanas, ya que nuestros medios de vida están vinculados y se basan en las funciones y valores que proporciona la biosfera. Si se permite que la tendencia de presiones crecientes continúe sin intervención, la salud humana, el bienestar y las economías podrían verse afectados tanto como los habitantes del ecosistema. Dado que los lagos son los

sistemas ampliamente utilizados y vulnerables, abordar estos problemas multifacéticos requerirá mirar más allá del sector científico para enfrentar los desafíos presentes y futuros.

En esta tesis, la investigación rastrea la relación causa-efecto desde 1) la ocurrencia de eventos extremos 2) sus implicaciones en las funciones del ecosistema 3) el efecto en el suministro de servicios del ecosistema hasta 4) las implicaciones que podrían tener las colaboraciones intersectoriales en la remediación del ecosistema. Esto se lleva a cabo mediante un enfoque interdisciplinario en el que cada capítulo aborda diversos aspectos de esta cadena de causa-efecto.

El **capítulo uno** investigó las implicaciones de los estresores climáticos individuales y coincidentes a través de un experimento de microcosmos de diseño factorial completo. En términos de la tesis general, este capítulo se centró en la relación causa-efecto de la ocurrencia de eventos extremos en el funcionamiento del ecosistema. Se midieron los efectos de un evento de calentamiento (presión continua), un evento de precipitación (presión puntual) y una combinación de ambos en una comunidad de fitoplancton compuesta por *Anabaena flos-aquae* (cianobacteria), *Chlorella vulgaris* (alga verde) y *Synedra* (diatomea). El tratamiento de calentamiento individual resultó en el efecto esperado de que la cianobacteria se convirtiera en la especie dominante. El evento de precipitación, por el contrario, tuvo un efecto transitorio de corta duración en la abundancia de fitoplancton. Finalmente, el tratamiento combinado de un evento de calentamiento y un evento de precipitación produjo un efecto general menor que el observado con los eventos individuales. Esta situación de evento coincidente no tuvo el efecto aditivo, multiplicador o sinérgico que se esperaba con aumentos significativos en la comunidad de fitoplancton. El diseño del experimento se basó en las condiciones medias del verano neerlandés, incluida la composición de la comunidad de algas y los tratamientos climáticos aplicados. Si bien los resultados de este experimento no se pueden traducir directamente a sistemas lacustres similares, los resultados proporcionan información sobre los mecanismos en los que los sistemas lacustres experimentan efectos mitigadores cuando se aplican presiones concomitantes. Se ha planteado la hipótesis de que la resiliencia intrínseca de los sistemas complejos es capaz de disminuir el impacto de las presiones. Con la tendencia cada vez más intensa de los fenómenos climáticos extremos junto con otras presiones, queda la pregunta de hasta qué punto los sistemas de agua dulce serán capaces de resistir la embestida de las presiones antes de que la continua degradación provoque el colapso del ecosistema.

El **capítulo dos** evaluó los impactos que la pandemia de coronavirus ("COVID-19") ha tenido en las interacciones humanas con sistemas lacustres en regiones altamente urbanizadas. Dentro de la cadena causa-efecto, este capítulo se centró en la ocurrencia de un evento extremo (la pandemia), su efecto en las funciones de ecosistemas acuáticos y los impactos posteriores en el suministro de servicios ecosistémicos. Las recomendaciones para las acciones de gestión formuladas en este capítulo también comienzan a abordar el cuarto componente de la cadena de causa-efecto sobre la remediación. El cambio repentino y generalizado en los comportamientos humanos debido a las normas de salud, provoco distintos cambios en las interacciones que ocurrieron con los ecosistemas acuáticos (tanto en aumento como en disminución según las normas locales de movilidad que se aplicaron). En primer lugar, el efecto de la pandemia podría atribuirse directamente a su efecto sobre la explotación de los servicios de los ecosistemas acuáticos, como se demostró en cuatro estudios de caso. Por ejemplo, el primer estudio sobre la calidad del agua de los canales en Ámsterdam, Países Bajos, reveló que la disminución del tráfico de embarcaciones favoreció el aumento de la claridad del agua junto con el establecimiento de vegetación sumergida que creó nuevas áreas de hábitat. Los otros tres estudios de caso (uso de aguas para baño, pesca recreativa y parques nacionales) demostraron situaciones con una mayor demanda de servicios ecosistémicos. Esto podría deberse a que la pandemia de COVID-19 instigó un movimiento para buscar consuelo en la naturaleza, especialmente porque muchos otros lugares (por ejemplo, parques de diversiones, viajes de vacaciones, etc.) no eran accesibles durante los períodos de confinamiento. En segundo lugar, los estudios de casos ilustraron la retroalimentación dentro de estos sistemas humano-naturaleza. Por ejemplo, con los canales, las presiones de navegación ejercidas sobre el sistema se hicieron evidentes una vez que la mayoría de la navegación motorizada cesó en el sistema y se restauró otro servicio ecosistémico (el hábitat de las especies). Los tres estudios de caso de recreación también ilustraron cómo un aumento en el uso humano de los servicios puede conducir a una disminución en las funciones del ecosistema, especialmente si no se aplican las mejores prácticas. Durante este período de COVID-19, ha habido oportunidades para que las personas vuelvan a familiarizar con sus ecosistemas de agua locales y recuerden el valor que dichos ecosistemas pueden proporcionar. Tomar medidas para mantener el alto aprecio y consideración que más personas le están otorgando a los sistemas naturales en el futuro podría ser un punto de inflexión para establecer prácticas humanas más sostenibles y reducir las presiones que se ejercen sobre ellos.

El **capítulo tres** se basa en el juego serio "Flipping Lakes", que diseñé y creé junto un campanero de trabajo. En términos de la cadena de causa-efecto de tesis, este juego rastrea la totalidad de la cadena de causa-efecto desde la ocurrencia de presiones extremas hasta la implementación de intervenciones de gestión. A través de la interacción con el juego, los jugadores se comprometieron con los componentes de causa y efecto al actuar como un "administrador de cuencas hidrográficas" encargado de preservar el estado limpio de los lagos del juego, manteniendo así la capacidad de estos cuerpos de agua para brindar servicios ecosistémicos. Desde un punto de vista teórico, este juego permite a los jugadores ver las interacciones completas de causa y efecto a medida que se desarrollan, incluso cuando en la vida real las implicaciones pueden ocurrir durante largos períodos de tiempo o ser difíciles de descifrar. La capacidad de personalización del juego para "construir sus propias cuencas" permite abundantes oportunidades para que los jugadores simulen un sistema específico, creen una cuenca ficticia o exploren varias combinaciones de las mismas. Además, el juego serio actúa tanto como una herramienta para aumentar la educación ambiental de los jugadores y como un soporte visual para las discusiones intersectoriales. El juego se jugó en numerosos lugares para evaluar la eficacia de su impacto en la educación ambiental. Con los estudiantes universitarios, las autoevaluaciones de los jugadores revelaron una mejor comprensión de conceptos tales como eventos climáticos extremos, estados estables alternativos y medidas proactivas. La aportación cualitativa de la administración universitaria y de profesionales de la ciencia de lagos expresaron su apoyo a la aplicación de juegos serios para transmitir conocimientos, particularmente en este formato de juego accesible donde los conceptos de "jugar un juego" son relativamente universales para la mayoría de las personas. Los ciudadanos y las partes interesadas de los lagos y la cuenca en general pueden ser valiosos colaboradores para recopilar conocimientos, desarrollar planes de gestión personalizados e implementar intervenciones de gestión. Utilizar herramientas que faciliten el acceso a los conceptos de la ciencia y gestión de los lagos, así como la reducción de las barreras a las discusiones técnicas, puede llevar a una mayor participación de la comunidad. De esta manera, una mayor participación y apropiación de los planes de intervención puede aumentar notablemente su eficacia. Ante los desafíos que actualmente afectan a los lagos y sus cuencas, trabajar activamente para incorporar a las partes interesadas en la toma de decisiones e implementación puede ser de gran ayuda.

En el tema de las colaboraciones intersectoriales, el **capítulo cuatro** investigó el grado de (des)conexión entre los científicos de lagos y los administradores, junto con los métodos para estrechar aún más los sectores. En la cadena de causa-efecto de la tesis, este capítulo se centró en las colaboraciones intersectoriales para la gestión de lagos en el contexto de presiones continuas (por ejemplo, eventos extremos), las funciones del ecosistema y la provisión de servicios. Dada la magnitud de la influencia que los eventos extremos pueden tener sobre los lagos y, posteriormente, tanto sobre la biosfera como sobre las comunidades antropogénicas, poder mitigar o evitar los efectos negativos requerirá conocimiento y planificación intersectorial. La encuesta en línea dirigida a los administradores de lagos se desarrolló para obtener su perspectiva sobre cuáles son los principales desafíos que afectan la gestión de lagos, cuáles son los objetivos de la gestión, qué papel desempeñan la ciencia y los científicos en la gestión de lagos y cómo las colaboraciones podrían mejorarse. Las respuestas regionales de América del Norte y de Europa demostraron superposiciones y disparidades entre las respuestas acumuladas. Por ejemplo, se exhibieron tendencias similares entre las regiones con respecto a qué desafíos están afectando a los ecosistemas lacustres (degradación del hábitat y especies invasoras) y qué barreras están obstaculizando las colaboraciones (financiamiento). Por el contrario, hubo desviaciones entre las dos regiones, como se demostró a través de respuestas diferentes en cuanto al papel que desempeñan los científicos en las discusiones de gestión en la actualidad y las oportunidades futuras para una mayor participación (los gestores de América del Norte vieron numerosas oportunidades para involucrar a los científicos en la actualidad y en el futuro, mientras que los gestores europeos involucran a los científicos para tareas específicas y percibieron pocas oportunidades para una mayor participación). Las diferentes circunstancias entre las dos regiones (p. ej., leyes y políticas rectoras, valores sociales generales, diferencias en los sistemas biogeoquímicos locales, etc.) podrían explicar las desviaciones. Estudios previos y numerosos proyectos intersectoriales han establecido varios métodos para colaborar, aunque no hay un enfoque único adecuado para cada asociación entre ciencia y gestión. Reconociendo de los hallazgos de la encuesta, estos métodos deben adaptarse a la situación regional en la que trabajan los gestores. La co-creación de marcos de colaboración y desarrollo de conocimientos podría avanzar hacia la consecución los objetivos de gestión de lagos, especialmente en un mundo extremo.

La multitud de presiones que afectan a los sistemas lacustres de agua dulce han resultado en una tendencia mundial de degradación prolongada y sostenida. La intensificación de los eventos climáticos extremos y la persistencia del estrés antropogénico es motivo de preocupación, particularmente con el grado prolongado y sostenido de degradación ya presente, ya que estas presiones extremas presentan desafíos que afectan a la biosfera y las comunidades humanas. Mantener los enfoques statu quo para utilizar, estudiar y gestionar los lagos no será suficiente para mejorar o preservar la salud y las funciones de los ecosistemas en el futuro. Navegar por el filo de la navaja para mantener las funciones y servicios de los lagos en un mundo extremo requiere métodos informados, proactivos, inclusivos y holísticos. Reconociendo la urgencia de la situación y adaptando los enfoques utilizados para esta nueva realidad, la biosfera y las comunidades antropogénicas dependientes pueden ser capaces de resistir los extremos.

Thesis Summary

The delineation of the current geological epoch as the “Anthropocene,” derived from the prefix “anthro-” meaning “human,” aptly summarizes the sheer magnitude in which humans have affected the biosphere. For many ecosystems, these pressures have caused long-term degradations to their health and functions. Freshwater systems such as lakes are particularly susceptible as these lentic water bodies act as sentinels of change in the region by accumulating information from the whole catchment. With pressures from anthropogenic actions and climatic scenarios projected to continue, if not intensify, in the coming decades, there is concern regarding the impairment of lake ecosystems.

Of the climatic projections, one of the more recent concerns is the intensifying frequency and severity of extreme climatic events ("ECEs"), or a climatic event such as a heatwave or precipitation that is in the tail ends (e.g. 99th percentile) of the distribution curve for that region or time of year. The potential for these events to instigate disproportionate disruptions within freshwater systems worldwide can be significant. Paired with other, non-climatic pressures derived from human actions, such as wide-spread land use change and pandemic outbreaks, there can be multiple pressures affecting the biosphere sequentially or in tandem. Depending upon the nature of the pressure, these can be categorized as "pulse" stressors which are generally short-lived events, such as heatwaves or extreme precipitation, and "press" stressors which have a long-lasting or chronic duration, such as ecosystem alterations (e.g. urbanization, dam construction, etc.) or climate change.

Degradation of systems presents challenges not only for the biosphere itself but for human communities as our livelihoods are tied to and built upon the functions and values that the biosphere provides. If the trend of increasing pressures is permitted to continue without intervention, human health, well-being and economies could be impacted just as much as the ecosystem inhabitants. With lakes being the abundantly utilized and vulnerable systems that they are, approaching these multifaceted problems will require looking beyond just the science sector to address present and future challenges.

In this thesis, the research traces the cause-effect relationship from 1) the occurrence of extreme event(s) to 2) their implications on ecosystem functions to 3) the effect on ecosystem service provisioning and 4) the implications that intersectoral collaborations could have on ecosystem remediation. This is conducted through an interdisciplinary approach with each chapter tackling various aspects of this cause-effect chain.

Chapter one investigated the implications of individual and coinciding climatic stressors through a full-factorial microcosm experiment. In terms of the overall thesis, this chapter focused on the cause-effect relationship of extreme event occurrences on ecosystem functioning. The applications of a warming event (press pressure), a precipitation event (pulse pressure) and a combination of both were measured against the reactions of a phytoplankton community comprised of *Anabaena flos-aquae* (cyanobacterium), *Chlorella vulgaris* (green alga) and *Synedra* (diatom). Within the microcosms, the individual warming treatment resulted in the anticipated outcome of the cyanobacterium becoming the dominant species. The precipitation event, in contrast, had a short-lived transient effect on phytoplankton abundance. Finally, the combined treatment of a warming event and a precipitation event yielded an overall effect that was less than that observed with the individual events. This situation of a coinciding event did not have the additive, multiplicative or synergistic effect that was anticipated via significant increases in the phytoplankton community. The design of the experiment was based upon average Dutch summer conditions, including the algal community composition and the climatic treatments that were applied. While the subsequent results from this experiment cannot be directly translated into similar lake systems, the outcome provides insights into mechanisms wherein lake systems experience mitigating effects when coinciding pressures were applied. It has hypothesized that the resilience intrinsic to complex systems are capable of decreasing the impact of pressures. With the intensifying trend of extreme climatic events in conjunction with other pressures, the question remains to what extent freshwater systems will be capable of withstanding the onslaught of pressures before the continued degradation causes an ecosystem collapse.

Chapter two assessed the impacts that the coronavirus pandemic ("COVID-19") has had on human interactions with lake systems in select highly urbanized regions. Within the cause-effect chain, this chapter focused on the occurrence of an extreme event (the pandemic), its effect on aquatic functions and the subsequent impacts on ecosystem service provisioning. The recommendations for management actions that were formulated in this chapter also begin to address the fourth component of the cause-effect chain on remediation. Based on the sudden and wide-spread shift in human behaviors due to health regulations, there were distinct changes in the interactions occurring with aquatic systems (both increasing and decreasing depending upon the local mobility regulations that were applied). Firstly, the effect of the pandemic could be directly traced to its effect on aquatic ecosystem service exploitation, as demonstrated in four case studies. For example, the first study on the water quality of canals in Amsterdam, the Netherlands revealed that decreased boat traffic supported the increase in water clarity along with establishment of submerged vegetation which created habitat area. The other three case studies (bathing water use, recreational fishing and national parks) demonstrated situations with an increased demand for ecosystem services. This could have been due to the COVID-19 pandemic instigating a movement towards seeking solace in nature, especially as many other locales (e.g. amusement parks, holiday trips, etc.) were not accessible during lockdown periods. Secondly, the case studies illustrated feedback within these human-nature systems. For example, with the canals, the boating pressures exerted upon the system became evident once the majority of motorized boating ceased in the system and another ecosystem service (species habitat) was restored. The three recreation case studies also illustrated how an increase in human use of the services can lead to decreases in ecosystem functions, especially if best practices (e.g. "leave no trace" principles) are not applied. During this COVID-19 period, there have been opportunities for people to become reacquainted with their local water systems and to recall the value that such systems can provide. Taking steps to maintain the high esteem and consideration that more people are currently placing on natural systems going forward could be a turning point in establishing more sustainable human practices and reducing the pressures being exerted upon them.

Chapter three is based on the serious game "Flipping Lakes" which I co-designed and created with a colleague. In terms of the thesis cause-effect chain, this game traces the entirety of the cause-effect chain starting with the occurrence of extreme pressures to the implementations of management interventions. Through interacting with the game, players were engaged with the cause-effect components by acting as a "catchment manager" tasked with preserving the clear state of the game's lakes, thus maintaining the capacity of these water bodies to provide ecosystem services. From a theoretical standpoint, this game permits players to view the full cause-effect interactions as they play out, even when in real life the implications could occur over long time periods or be challenging to decipher. Customizability of the game for "build your own catchments" permits abundant opportunity for players to simulate a specific system, create a fictitious catchment or to explore various combinations thereof. In addition, the serious game acts as a tool for both increasing the environmental literacy of players and as a visual support for intersectoral discussions. The game was played in numerous venues to assess the efficacy of its environmental literacy impact. With university students, self-assessments by players revealed an improved comprehension of concepts such as extreme climatic events, alternative stable states and proactive measures. Qualitative input from university administration and from lake science professionals expressed support for the application of serious games for transmitting knowledge, particularly in this accessible game format wherein the concepts of "playing a game" are relatively universal for a majority of people. Citizens and stakeholders of lakes and the broader catchment can be valuable collaborators for gathering knowledge, developing tailored management plans and implementing management interventions. Utilizing tools that make the concepts of lake science and management more readily available, as well as lowering barriers to technical discussions, can lead to more involvement of the community. In this way, enhanced involvement and ownership of intervention plans can markedly increase their effectiveness. With the challenges currently affecting lakes and their catchments, actively working to incorporate stakeholders in decision-making and implementation can be helpful.

In the theme of intersectoral collaborations, **chapter four** investigated the extent of (dis)connection between lake scientists and managers along with methods to further bridge the sectors. In the thesis cause-effect chain, this chapter focused on intersectoral collaborations for lake management set in the context of ongoing pressures (e.g. extreme events), ecosystem functions and service provisioning. Given the extent of influence that extreme events can have on lakes and subsequently on both the biosphere and anthropogenic communities, being able to mitigate or avoid the negative effects will require intersectoral knowledge and planning. The online survey targeted at lake managers was developed to glean their perspective on what are the main challenges affecting lake management, what are the goal(s) of management, what role(s) do science and scientists play in lake management as well as how collaborations could be improved. The regional responses from North America and from Europe demonstrated overlap and disparities between the responses accumulated. For example, similar trends were exhibited between the regions regarding what challenges are affecting lake ecosystems (habitat degradation and invasive species) and which barriers are hindering collaborations (funding). Conversely, there were deviations between the two regions as demonstrated through differing responses to what the role(s) of scientists in management discussions are presently and what future opportunities there are for further involvement (North American managers saw numerous opportunities for involving scientists presently and in the future, European managers engage scientists for select tasks with little perceived opportunity for further involvement). Different circumstances between the two regions (e.g. guiding laws and policies, overall societal values, local biogeochemical system difference, etc.) could provide explanations for the deviations. Previous studies and numerous intersectoral projects have established various methods for collaborating, though no one single approach is suitable for every science-management partnership. In recognition of the survey findings, these methods should be adapted to the regional situation that managers are working within. Co-creation of collaboration frameworks and knowledge development could make strides towards achieving lake management goals, especially in an extreme world. The multitudes of pressures affecting freshwater lake systems has resulted in a global trend of prolonged and sustained degradation. The intensification of ECEs and the persistence of anthropogenic stress is a cause for concern, particularly with the prolonged and sustained degree of degradation already present, as these extreme pressures present challenges that affect the biosphere and human communities. Maintaining status quo approaches to utilizing, studying and managing lakes will not be sufficient for improving or preserving ecosystem health and functions in the future. Navigating the razor's edge of maintained lake functions and services in an extreme world requires informed, proactive, inclusive and holistic methods. By recognizing the urgency of the situation and adapting the approaches used for this new reality, the biosphere and dependent anthropogenic communities may be able to weather the extremes.

General Introduction

1. The Anthropocene and the environment

The delineation of the current geological epoch as the "Anthropocene" (Trischler, 2016), derived from the prefix "anthro-" meaning "human," aptly summarizes the sheer magnitude in which humans have affected the biosphere in recent times (Bowler et al., 2020). While humans have demonstrated an immense propensity for ingenuity, as demonstrated through successful establishment of communities across all continents and habitat types, the same trait has propagated an extensive societal mindset that is technologically-advanced yet environmentally-distant (Folke et al., 2021). Perceived divisions between humans and the rest of nature have permitted disconnects that frequently cause a lack of consideration for the environment in anthropogenic actions (Brymer et al., 2019; Santiago Fink, 2016). In turn, human (in)actions can result in abundant pressures being exerted upon the biosphere worldwide that extend past those of cyclical climatic patterns or the inherent variability of individual ecosystems (Folke et al., 2021). At the current rate of pressure exertion from extensive, concentrated and persistent anthropogenic actions (Heino et al., 2021), such as with land use change and human-induced shifting of the climate, there is concern over the continued functioning of the biosphere. Freshwater lake ecosystems, often perceived as sentinels of the catchment, exemplify the culmination of these pressures in ecological, societal, political and economic contexts (Adrian et al., 2009; Moss, 2011).

1.1 "Press" versus "pulse" categorization

The diversity of pressures both ongoing and anticipated can have a broad range of implications on the various functions and uses of freshwater systems, especially lakes. These pressures can be generally categorized according to the duration of their occurrence. For instance, "press" stressors are classified as pressures that are sustained over a period of time (Bender et al., 1984). These long-term stressors can include natural and human induced pressures, such as climate trends or eutrophication. Societal pressures can also classify as "press" stressors if they have been exerted over a long period of time, such as land use change (e.g. water quality decline from urban intensification; Song et al., 2020) or in-system alterations (e.g. construction of dams; Grill et al., 2019).

In contrast, "pulse" stressors are defined as pressures that are relatively brief or short lived (Bender et al., 1984). Many extreme climatic events ("ECEs"; Smith, 2011) qualify as pulse pressures, including heatwaves and precipitation events. In a European context, projected trends include large increases in extreme precipitation events (Madsen et al., 2014) along with more frequent and longer extreme summer heatwaves (McGregor et al., 2005; Woolway et al., 2021). In addition to climate-based pulse stressors, these pressures can also originate from societal actions such as sewage overflows (Canobbio et al., 2009).

1.2 Climatic pressures

Globally there is a trend of diminishing aquatic habitat quality and quantity as well as species diversity (Gozlan et al., 2019) attributed in part to increasing and persistent pressures from climate change (Moss, 2011). In addition to the shifts in climatic averages, ECEs have been a growing concern in recent years; in comparison to long-term changes to the average climate, ECEs are a concern due to the intensity of the events, the frequency at which they are anticipated to occur and the lasting impacts that the occurrences can have (e.g. McGregor et al., 2005). For instance, Northwestern Europe has already experienced shifts with climatic temperatures influencing the intensity of short-term extreme precipitation events (Lenderink et al., 2011;

Lenderink & van Meijgaard, 2008). The actual manifestation of climate change, though, will be region-dependent. Therefore, the classification of intensified climatic events as "extreme" or not will be dependent upon the definitions of each region and how climatic events manifest going forward (e.g. Ren et al., 2012).

As of August 2021, the United Nation's Intergovernmental Panel on Climate Change has classified the climate crisis, including the occurrence of ECEs along with altered climatic averages, as a "code red" (Arora & Mishra, 2021). In lieu of the preventative and rehabilitative measures that are desperately needed to address and rectify the drivers of climate change, mitigation measures need to be taken to protect the remaining functions of natural systems (e.g. Ladwig et al., 2018).

1.3 Non-climatic pressures

In addition to anthropogenic-driven climate change, pressures can also originate more directly from anthropogenic actions; as stated previously, the delineation of the current epoch as the "Anthropocene" gives sentiment to the degree of influence that our historical and current societies and actions have had on the biosphere (Falkenmark et al., 2019). An array of chronic pressures that are systematically degrading the water quality of freshwater systems, such as lakes, have been well-documented over the years. The most prevalent challenges in Europe and Central Asia, for example, are press pressures that come from agricultural intensification and urbanization (IPBES, 2018). Eutrophication, particularly due to the indirect effects of human actions such as agricultural intensification, has been tied to the frequent occurrence of algal blooms (Paerl et al., 2020), of which the toxin-emitting cyanobacterial blooms frequently yield public attention (Lürling et al., 2017). Urbanization is a similarly potent press pressure in terms of effects on surface water systems as chronic degradation can occur due to 1) the direct introduction of materials into water bodies via infrastructure and 2) the indirect introduction from runoff via impermeable surfaces (e.g. large urban centers in the Laurentian Great Lakes region; (Mahdiyan et al., 2021; Seilheimer et al., 2007). These, though, are press stressors that have historically been affecting water systems. Humans are capable of instigating non-climatic extreme events with pulse pressures. For example, oil spills have ripple effects from surface water systems being exposed to contaminants, which effectively causes a decrease in water quality (e.g. Moskovchenko et al., 2009).

The pace of degradation as a result of a human-caused stressor can also occur swiftly, as was the case with the recent arrival of the COVID-19 pandemic. This phenomena relayed the sheer degree of influence that humans have on the biosphere over the course of the pandemic, which has left no facet of society or corner of the planet unaltered (e.g. Bates et al., 2020). In particular, the rapid shift of human activities during the "anthropause" period (e.g. pulse pressure) resulting from the most stringent of social-distancing and lockdown requirements has led to a slew of both positive and negative implications on ecosystem functions and inhabitants (e.g. Boroujeni et al., 2021).

1.4 Cumulative stressors

In addition to understanding the individual pressures that are affecting, if not directly impairing, the health and functions of freshwater systems, it will become important to have working knowledge regarding how the combination of these pressures will influence aquatic ecosystems (e.g. Ormerod et al., 2010; Spears, Chapman, Carvalho, Feld, et al., 2021; Spears, Chapman, Carvalho, Rankinen, et al., 2021). The scale at which global climate change, including more pervasive extreme climatic events, and regional human impacts are causing extensive degradation has resulted in wide-spread impairment of a broad range of biosphere systems (Bergstrom et al., 2021).

With lakes as sentinels for the entire catchment (Adrian et al., 2009), these water bodies can concentrate and illustrate the degradation that is occurring throughout (Schindler, 2009). The combination of pressure over time (e.g. long-term degradation of the system paired with an extreme climatic event) or with coinciding events (e.g. two extreme climatic events) can lead to cumulative stress which is additive or synergistic (Folt et al., 1999). This has been experienced, for instance, in microcosm studies (Christensen et al., 2006) and modeled simulations (e.g. S. D. P. Smith et al., 2019).

In contrast, there is the potential for simultaneously occurring events to have antagonistic effects (Folt et al., 1999). According to Jackson et al. (2016), multiple stressors in a lake system have, on average, an antagonistic effect. This was attributed to the capacity of lake systems to adapt to multiple stressors due to the diversity of the aquatic community. However, novel and diverse systems are not immune to multiple stressor situations; cumulative pressure stemming from the co-occurrence of pressures, including that of press-pulse stressor combinations, can hamper the functions and diversity of well-adapted communities (e.g. Harris et al., 2018). Additionally, the complexity that arises from multiple stressors, especially when the pressures may differ on various time and geographic scales, can lead to gaps in our knowledge unless research specifically addresses this (e.g. Sabater et al., 2021).

2. Extreme events on ecosystem functions

The occurrences of extreme events, both climatic and otherwise, are capable of interrupting the abiotic and biotic processes that underlie lake ecosystem functions. Taking Europe as an example, an amalgamation of both climate and anthropogenic stressors leaves the lakes of this region susceptible to abundant pressures. To begin combating these pressures, the European Union's Water Framework Directive ("WFD") legislation mandates that all qualifying water bodies achieve "good ecological status" by the end of the management cycles (Kallis & Butler, 2001). Through monitoring of established parameters and their level categorizations, progress towards a "good" status can be observed. Unfortunately, given heightened concerns related to the intensification of ECEs in recent decades, defining the extent to which extreme climate-based pressures are capable of hampering lake functions, and subsequently thwarting the possibility of reaching the established WFD goal, has become a pertinent question. This is particularly of interest for regions such as Europe wherein many lakes have been exposed to sources of continuous degradation, such as extensive urbanization.

2.1 Abiotic repercussions of extreme events

Changes to lake chemical processes as a consequence of climatic pressures have the potential to instigate significant ecosystem disruptions (Calderó-Pascual et al., 2020). Between extreme precipitation and warming events there can be ramifications on, for example, lake nutrient loading, water coloring, turbidity and water temperature. The increased runoff from extreme precipitation (Jennings et al., 2012) can affect surface water systems in a number of ways and is hypothesized to vary with the amount of anthropogenic land use in the watershed (Stockwell et al., 2020). Nutrient influxes can occur due to the runoff-instigated soil mobilization within the catchment, leading to large, diffuse depositions into receiving water systems (Ockenden et al., 2016). For example, a single extreme precipitation event can account for a significant portion of the total annual nutrient loading (Zwart et al., 2017). Nutrient pulses can boost phytoplankton growth on a short-term temporal scale, especially in oligotrophic systems (Carrillo et al., 2017; Morabito et al., 2018). Runoff into a system can also cause brownification (Feuchtmayr et al., 2019), which can lead to a decrease in light availability and an increase in water temperature (Weyhenmeyer et al., 2004). Similarly, the turbidity of a system could be altered due to runoff, stimulating the re-suspension of *in situ* sediments (Kasprzak et al., 2017). In turn, this can instigate decreases in water transparency (Kasprzak et al., 2017) and in light availability (Stockwell et al., 2020). Contingent on the hydrological and catchment composition, extreme precipitation will also impact the lake residence time of water and thereby nutrients and phytoplankton in a water system. A large influx of water into the system, for instance, can dilute the concentrations of nutrients within the lake (Cobbaert et al., 2014). Further, surface water bodies with outlets can experience a flushing effect with outflowing waters carrying nutrients from the system (Ho & Michalak, 2020). In such cases, an extreme precipitation event could assist with improvement of the overall water quality.

Warming, such as through heatwaves, can influence chemical processes through different routes. These events can have a direct and noticeable impact on water temperature, which in turn can strengthen stratification within the water columns (Chen et al., 2019). Nutrients stored in sediments can also become bioavailable at higher water temperatures. This can occur when a stabilized water column promotes the release of nutrients from the substrate, which can then be redistributed in the lake from subsequent mixing of the water column (De Senerpont Domis et al., 2013; Velthuis et al., 2017; Wagner & Adrian, 2009).

The outcomes of climatic stressor effects within a lake can be dependent upon the local situation, such as regional location, antecedent lake conditions, time of year and event severity amongst other factors. It can therefore be challenging to predict the impact that an event or pressure will have on lake chemical processes given the numerous and contradictory pressures that increased precipitation, runoff and warming can present.

2.2 Biotic repercussions of extreme events

Climatic stressors have been observed to have direct impacts across different trophic levels of freshwater lake systems (e.g. Kangur et al., 2013; Li et al., 2017). In aquatic systems, a prime interest lies in the potential impact of climatic stressors on phytoplankton, as disruption within the primary food web base may lead to shifts in seasonal successional dynamics (Sommer et al., 2012) and have cascading effects on other trophic levels (De Senerpont Domis et al., 2007). Specifically, proliferation of cyanobacteria is a concern with their low nutritional value (De Senerpont Domis et al., 2007) and resistance to grazing (Lürling et al., 2013), effectively hindering energy transfer in the food web. These additional pressures from climatic stressors in an already degraded lake ecosystem could further disrupt the ecosystem processes and phytoplankton dynamics (e.g. Bartosiewicz et al., 2019). The consequences of an extreme precipitation event in periods of prolonged warming on a lake system can be conducive to phytoplankton proliferation. For instance, as the productivity of phytoplankton in lake systems is contingent on nutrient availability (Sommer et al., 2012), nutrient additions from precipitation runoff and warming-driven internal cycling can support bloom formation (De Senerpont Domis et al., 2013). Given the anticipated frequency of short-duration storms in Northwestern Europe during summer (Haarsma et al., 2013; Liu et al., 2021), subsequent nutrient influxes could support such algal growth in lakes (Kosten et al., 2012). Temperate eutrophic systems in particular have had significantly bolstered phytoplankton biomasses owing to high availability of nutrients and warm temperatures (Lürling et al., 2018). Under such circumstances there is a selection effect of certain functional traits. For instance, cyanobacteria that have buoyancy regulation and grazing defenses can utilize these traits to outcompete other functional groups (Lürling et al., 2013). Shifts in light availability due to alterations of turbidity and brownification (Bergstrom et al., 2021; Perga et al., 2018) can select for phytoplankton species with a competitive advantage (Ekvall et al., 2013; Feuchtmayr et al., 2019), such as for cyanobacteria with the capacity for vertical movement (Walsby et al., 1991). Water temperature, one of the key factors determining phytoplankton dynamics, can be elevated both directly by warming and indirectly by precipitation-induced turbidity and heat absorbance (Williamson et al., 2016). Previous studies demonstrate that the optimal growth temperature for cyanobacteria can be higher than that of other phytoplankton species (De Senerpont Domis et al., 2007) and, as a result, cyanobacteria can outcompete other species and dominate the phytoplankton community under extreme warming conditions (Kosten et al., 2012).

However, while some aspects of climatic pressures might be advantageous for phytoplankton growth, not all implications of these events may be favorable. Precipitation runoff also presents the possibilities of dilution, cooling and flushing in a lake, all of which can affect otherwise ideal conditions for cyanobacteria as well as other phytoplankton species. For example, the addition of water to a lake can cause a dilution effect due to the nutrients and solutes becoming less concentrated (Cobbaert et al., 2014). Precipitation events can also have a cooling effect, leading to a lowering of the overall system water temperature (e.g. Wood et al., 2017). While some phytoplankton groups such as diatoms are capable of handling the lower temperatures (Velthuis et al., 2017), cyanobacteria are less competitive in cooler temperatures (De Senerpont Domis et al., 2007; Huber et al., 2012). A shift in the dominant functional group can occur as a result. Flushing, in contrast, could remove the nutrients from the system (Stockwell et al., 2020), along with phytoplankton, eliminating these from the in-lake community.

3. Human-nature systems

The influence of extreme pressures on lakes does not end at ecological functions, but rather has intersectoral implications due to the wide-reaching value of lakes. The role of lakes as “sentinels” of the catchment traces the direct connection between the actions of humans to the effect that it has on the biosphere, even if the anthropogenic activities are unintentionally or unknowingly causing degradation. Rather than viewing this connection as an isolated incident or declaring humans as merely another type of stressor on the ecological functions of lakes, this flow of pressures from humans to lakes is part of a two-way feedback (Folke et al., 2021).

Lakes are a prime example of human-nature systems as these water bodies are interactive with the give and take of pressures with anthropogenic communities. The presence and provisioning of ecosystem services, or the benefits specifically derived by people from the functions or existence of a given ecosystem, is widely known given the personal and economic valuation of these services (Comberti et al., 2015). In itself, the flow of values from lakes to people is a pathway for the lake to provide the services as well as for people to exert pressure through the unsustainable demand of services (i.e. in relation to the lake’s supply; e.g. Seelen et al., 2019).

In the other direction, it is possible for lakes to receive positive feedback from people via “services to ecosystem,” or the actions that humans can take to promote the functioning of services (Comberti et al., 2015). Such pointed services toward nature can occur through, for example, specific interventions. However, in order for humans to make concerted efforts towards supporting ecosystems (and thus in turn securing the continued provisioning of ecosystem services which can return a net benefit to anthropogenic communities), there must be fundamental understanding of how humans and ecosystems are interlinked along with the different pathways in which influence can flow.

Frameworks have been created to help elucidate these connections, thereby highlighting how we can become more efficient stewards and beneficiaries of natural ecosystems. For example, Liu et al. (2021) developed the "coupled human and natural systems" framework to outline the complexity of human-nature interactions across spatial, temporal and sectoral scales. Haimeng et al. (2020) further expound upon this framework to illustrate the nested, interconnected nature of human-nature relationships in their "coupled human and nature cube" framework. Of course, each natural aquatic system and challenge is highly specialized, requiring that the unique set of factors and levels for that water system and human community is accounted for. For example, multi-cultural communities can present another layer of complexity within the human-nature setting, particularly if there are deviating values present within the local populace (Negev, 2019). If nothing else, having these example frameworks emphasizes the point that there are abundant interactions occurring between human communities and natural systems. Therefore, having a baseline knowledge of how communities and the aquatic system interact can support further insight into the feedbacks happening.

4. Extreme events on ecosystem service provisioning

Perhaps the most prominent interaction of people with nature occurs through the use of ecosystem services (e.g. Allan et al., 2013). Of the various services that can be provided by lakes, the highly visible ones are the cultural (e.g. recreation, aesthetics, cultural significance, research) and provisioning services (e.g. food, drinking water, building materials; Haines-Young & Potschin, 2010). Additionally, while regulating services such as water filtration and contaminant bioremediation may not be as readily visible to the non-scientific populace, the service of "species habitat" is accounted for in (inter)national legislation. For instance, the Water Framework Directive ("WFD") is based on the uniform consideration of protecting aquatic species habitat through its established guidelines and parameter targets (Tolonen et al., 2014). Further consideration of other services in the WFD can also be factored in through deferments as some existing services, such as boat transportation in surface waters, can hamper the achievement of the established habitat targets.

While ecosystem services may be perceived as having no initial labor or monetary costs, their economic exploitation is highly dependent upon having a continuous (i.e. uninterrupted) or timely-available (e.g. seasonally-available) supply, which could require some stewardship of the system. Some communities, such as small towns or resort-based cities, are economically dependent upon lake services due to the majority of annual income coinciding with tourism or with the exporting of a specific good. In this case, the provisioning of services for human use can be derailed from pressures that degrade the underlying ecosystem functions responsible for creating the service. The current projections of climatic extremes in conjunction with other anthropogenic-caused pressures can lead to alterations in the timing of the service provisioning, if not preventing the service from being provided at all.

5. Ecosystem tipping points

In regards to the concerns over how extreme pressures are affecting lakes, there is the question as to what point lakes can continue operating before both the functions and subsequent service provision collapses. Between the degraded antecedent conditions of many lake systems globally in tandem with the bleak future projections of extremes, it will be important to understand the limits of lakes and to determine what the current status, or "state," of a system is. Recent decades have applied the concept of "tipping points" to explain the shifts in lake states (Langdon et al., 2016).

In terms of the impact that tipping points and shifting states have on the human population, there is evidence supporting the idea that some services will not be as readily provided by these ecosystems when the system is in a more degraded state, such as a eutrophic or hypereutrophic state (Hilt et al., 2017; Janssen et al., 2021). Further, lake theories of "alternative stable states" (Scheffer & van Nes, 2007) and "hysteresis" (van Nes et al., 2007) support that once a system enters another state (e.g. oligotrophic to eutrophic), the lake can be entrenched in that condition unless significant change is applied to revert it into a more desirable and less degraded state (e.g. Ibelings et al., 2007). While this may not apply to all systems, such as with shallow lakes frequently fluctuating between degraded and non-degraded states regardless of human forcing (e.g. Hobbs et al., 2012), there is the risk for these and other water body types to become more degraded under continued and intensifying pressure (e.g. Veraart et al., 2012).

6. Managing an extreme world

There is a balance between environmental limits and human uses that can be struck, as demonstrated by the "sustainability doughnut" concept (Capmourteres et al., 2019). This balance, deemed the "safe operating space," permits sustainable use for human needs while preserving the integrity of natural systems. At present, this safe operating space has been exceeded in numerous categories. Focusing on water ecosystems, this unsustainable exploitation and degradation are extensive problems due to the way water is foundational (or ingrained in) all environmental, social, political and economic aspects of ours and others' livelihoods; the exploitation of water for basic hygiene and health necessities along with commodities will track with the overpopulation of people globally and the demand for economically advantageous lifestyles, respectively (Langford, 2005). As mentioned previously, extreme pressures are also projected to become more disruptive in the future, especially for susceptible systems such as aquatic water bodies (e.g. Bahn et al., 2014). A fundamental change in both the way that the environment is perceived as well as protected will be tantamount to achieving any type of sustainable balance.

Management of these ecosystems becomes more significant when trying to handle the razor's edge of the multiple and competing considerations of the inherent water system, human needs and intensifying external pressures. In turn, intersectoral approaches are prerequisite for any chance to avoid toppling into pressure intensification, ecosystem collapse and falling short on human needs (Cormier et al., 2018). Specifically, with over-taxation of the natural systems, though particularly aquatic ones, is the norm in maintaining the lifestyle which most of the world currently prescribes, solutions will need to be based on more than just technology alone; they will also need to incorporate the aspects and functions of each unique ecosystem including the minimum for overall functionality (including diversity, species community numbers, water quality, water quantity and more) that nature inherently needs for a maintained existence (e.g. Santiago Fink, 2016). In other words, applying simple solutions according to engineering alone will no longer be sufficient, especially if there are no ecosystem benefits being provided and if the measure merely prolongs the inevitability of a collapse while masking the symptoms (e.g. Reid et al., 2018). Consideration with intersectoral approaches will be necessary especially with an emphasis on ecosystem needs and how we can more sustainably work within the safe operating space. The first step towards intersectoral approaches is to reconcile the deviating perspectives of scientists, managers and stakeholders to co-create a shared goal, plan and actions.

As lakes transcend multiple sectors and facilitate a number of uses, it is easy to imagine that a disconnect can occur anywhere within this complex network of cause-effect relationships. One prominent disconnect that commonly occurs is the failure to optimize science-management intersectoral collaborations (Dreelin & Rose, 2008). Science's role in investigating the mechanisms behind lake functions, the effects that pressures have and the recovery that interventions can have has resulted in a wealth of knowledge regarding our natural water systems. In turn, lake management is capable of developing and implementing interventions to improve the overall health, functions and uses of the water bodies. Unfortunately, barriers such as sectoral-specific jargon, mismatch between the sectoral goals and a lack of communication of knowledge has led to an underutilization of these sectors in collaboratively addressing lake challenges (Cvitanovic et al., 2016).

Concerted efforts from both sectors can initiate an integrated approach to addressing lake challenges. For example, adjusting management approaches to more readily integrate scientists and scientific knowledge can help foster more effective collaborations (e.g. Roux et al., 2006). Additionally, scientists can alter their knowledge communication methods to be more amenable for manager needs (e.g. Williams, 2015). These steps could promote informed decision-making which is requisite for counteracting the extensive degradation circumstances that have been and are expected to continue affecting lakes (Creed et al., 2016). Specifically, utilizing the best available and relevant science to inform lake management decision-making processes could be ideal for the array of pressures that affect the water bodies presently or are anticipated to do so in the future. While there have been instances of success stories of intersectoral collaborations (e.g. Bartram et al., 2002), not every approach will be suitable for every situation and thereby necessitates the discussion and tailoring of approaches between the included scientist and manager parties.

Related with intersectoral collaborations, there can also be disconnects between water professionals (i.e. scientists and managers) and stakeholders (i.e. community members, ecosystem service users, etc.). Pulling stakeholders into the collaboration could enrich the give-and-take of knowledge for developing informed management interventions (Franzén et al., 2015). To begin making this connection, it would be important for all participants to understand how lakes can function differently due to external stimuli and internal feedback (i.e. tipping points, alternative stable states and hysteresis), making communication of these topics to the services-dependent human communities key (e.g. Koroleva & Novak, 2020). It is paramount that this information is actively shared and that the environmental literacy of surrounding stakeholder groups is enhanced at every possible opportunity (e.g. Dean et al., 2016), though communicating scientifically or managerially complex topics can be challenging. Defining the most effective methods for communicating and educating about these topics will be important for holding inclusive, technical collaborations.

Global narratives towards climate change and its subsequent challenges should be on establishing governing rules in which remediation or reversing of climate change is the primary objective. It is with hope that this author looks towards a future where definitive actions are taken at all levels and by all communities. For this thesis, however, the research contents and discussion have been formulated under the assumption that climate change will be a continuing pressure in the coming decades and is therefore looking at methods to support the continued functioning of lakes and similar freshwater ecosystems in this reality.

7. Thesis chapters

Understanding the extent of implications that extreme events, degraded lake states and ecosystem service demand have on these aquatic ecosystems along with their connections to each other can begin elucidating key guidelines for addressing the grim climatic and societal projections. As summarized in this introduction, there are too many negative implications of degraded lake systems on the natural and built environment to not investigate the problem and to enact informed actions. This thesis traces the cause-effect relationship from 1) the occurrence of extreme event(s) to 2) their implications on ecosystem functions to 3) the resulting effect on ecosystem service provisioning and 4) the overall implications that intersectoral collaborations could have on ecosystem remediation. The four incorporated studies create an intersectoral overview of the problem and propose both insights and methods for developing solutions.

In **chapter one**, the link between extreme climatic event (ECE) occurrence and ecosystem functions was analyzed with a microcosm experiment. Responses of algal communities to an ECE event, an average climatic pressure and a combination of the two delves into the concern of coinciding pressures leading to impacts on lakes. We hypothesized that the combination of the warming scenario and the precipitation event would lead to the proliferation of the algal assemblage in comparison to the assemblages in microcosms that did not receive both treatments.

In **chapter two**, the consideration of pressures affecting the functions and services of aquatic ecosystems was reviewed with the COVID-19 anthropause event. As ECE pressures occur in tandem with other such disturbances, it is vital that the implication of these individual and coinciding pressures on water bodies is identified. In this chapter, the connections between the anthropause on the functions and ecosystem services of aquatic systems in urban areas is reviewed. Take-aways from the pandemic are translated for application in management.

In **chapter three**, translation of scientific concepts, management approaches and the impending future of ECEs was conducted using a serious game as a communication medium. The usefulness of such a tool in stimulating and supporting discussion with both aquatic professionals and citizens was analyzed. The potential applications of this tool for supporting other management planning endeavors are also outlined.

In **chapter four**, the connections between science and management were elucidated from lake manager perspectives. The roles of scientific information and of scientists with the development and implementation of lake management plans was elucidated. The potential of expanding these roles was also disclosed to elaborate on the potential for increasing intersectoral collaborations in future. We hypothesized that the challenges affecting lake management would vary between regions. Further, we hypothesized that there would be region-specific opportunities to expand the role of science in management processes.

In **the General Discussion**, I summarize the main findings of the studies and discuss points that should be expanded on.

Materials and Methods

In this section, an overview of the methods and materials used in chapters one through four are provided. Methods are outlined by fieldwork, laboratory methods, data gathering and statistical analyses. As the research questions behind the four chapters assessed different aspects on the extreme climatic event-ecosystem function-ecosystem services-intersectoral collaboration cause-effect relationship, there is little overlap between the chapters regarding the methods used.

1. Field site and sampling

1.1 Omloop Lake Field Site (Chapter One)

In chapter one, the treatments (temperature and precipitation simulations) and the phytoplankton species in the experimental microcosms were based on the conditions present in Omloop Lake, which is a hydrologically isolated, moderately deep (6.8m) and eutrophic lake system located in the southwest of the Netherlands (51.79242 N, 4.95114 E). The summer conditions of this lake are representative of many of the anthropogenically-created water bodies in the country. In line with regional trends, there is land-use induced nutrient enrichment leading to the subsequent eutrophic state of water bodies and an abundance of cyanobacteria.

1.1.1 Omloop Lake weather datasets

Water temperatures in the experimental microcosms were based on average and extreme summer temperatures using hourly air temperature data records (1951-2017) of the Royal Dutch Meteorological Institute's de Bilt weather station.

The soil runoff events were applied to microcosms to simulate the impacts of extreme precipitation events in the region. These events were based on daily precipitation values from the de Bilt weather station's 1906-2017 summer precipitation records.

1.1.2 Omloop Lake soil sampling

The soil samples from the shore of Omloop Lake were taken to simulate particulate material in overland runoff. Soil was gathered from the shoreline of the lake. Collected soil was homogenized before undergoing drying. Following this, soil was sifted to remove large organic material and for uniformity of the soil.

1.1.3 Omloop Lake phytoplankton composition

Each experimental microcosm was inoculated with a phytoplankton community consisting of cyanobacterium *Anabaena flos-aquae* (CCAP 1446/1C), green alga *Chlorella vulgaris* (UTEX 26) and diatom *Synedra sp* (from a 2009 field isolate from Lake Maarsseveen, The Netherlands, 52°08'32.2" N 005°04'53.7" E).

2. Laboratory methods

2.1 Microcosm treatments (Chapter One)

2.1.1 Microcosm temperature treatment

Air temperatures were converted to water temperatures with the Dutch surface water, yielding 18 ºC and 24 ºC for ambient and warm scenarios, respectively. Temperature treatments were administered through water baths containing a heating element (EHEIM 3619 300W heater, Deizisau, Germany) and an underwater pump (EHEIM compactON 1000, Deizisau, Germany). Water temperature was controlled with a custom climate control system (SpecView, Uckfield, United Kingdom) at +/- 0.5 ºC.

2.1.2 Microcosm precipitation treatment

Rainfall simulations were performed with the Wageningen University + Research Soil Physics and Land Management Group rainfall simulator to attain a realistic scenario of soil runoff volumes due to precipitation events. Simulation results informed the precipitation treatments administered to the microcosms. The runoff event was applied to microcosms on day 13 of the experiment.

2.2 Abiotic microcosm sampling (Chapter One)

2.2.1 Probe data

Water temperature, pH and dissolved oxygen were measured in the microcosms at the beginning of each sampling event using a WTW Multi 350i Field Meter (WTW, Weilheim, Germany).

Turbidity was measured from microcosm samples weekly with a WTW Turb430IR Meter (WTW, Weilheim, Germany).

2.2.2 Sampling method

Samples were collected from microcosms using sampling tubes. All sampled volumes were replaced with equivalent amounts of COMBO medium to compensate for the loss in water and nutrients. These samples were used to analyze both abiotic and biotic parameters of the microcosms.

2.2.3 Dissolved and particulate nutrient fractions

Samples were filtered with Aquadest glass microfiber filters (Whatman GF/F, Maidstone, United Kingdom). Filters were dried for 24 h at 60 °C before being stored in a desiccator. Filters for particulate phosphorus were incinerated at 550 °C for 20 minutes then autoclaved with a 2% potassium persulfate solution at 121 °C for 30 minutes. Resulting solutions were analyzed for phosphorus concentrations with a QuAAtro39 segmented flow analyzer (Seal Analytical, Rijen, the Netherlands). Particulate carbon and nitrogen fractions were determined from filter samples with a FLASH 2000 organic elemental analyzer (Brechbueler Incorporated, Interscience B.V., Breda, the Netherlands). Filtrate samples were stored at -20 ºC until run through an ASI-L Auto Sampler (Shimadzu, Kyoto, Japan). Phosphate, total oxidized nitrogen, nitrite, nitrate and ammonium concentration were quantified with a QuAAtro39 segmented flow analyzer. Dissolved organic carbon and dissolved inorganic carbon were measured weekly in a TOC-L Total Organic Carbon Analyzer (Shimadzu, Kyoto, Japan). Total phosphorus and total nitrogen were calculated through summation of the dissolved and particulate nutrient fractions.

2.3 Biotic microcosm sampling (Chapter One)

2.3.1 Community composition

The microcosm phytoplankton community composition was quantified each sampling day with a PhytoPAM fluorometer (WALZ, Effeltrich, Germany).

3. Processing of publicly available datasets

3.1 Boat traffic versus Water transparency (Chapter Two)

3.1.1 Boat traffic dataset

Data on boat traffic in Amsterdam canals has been collected as part of the municipality of Amsterdam's project "The Digital Canal". This programme outfitted boats with receivers that were tracked via remotely monitored sections of the canals.

3.1.2 Water transparency dataset

Water transparency data were averaged from biweekly Secchi disc readings collected by the Regional Public Water Authority Amstel, Gooi and Vecht as part of their water quality monitoring programme.

3.2 Annual fish license reporting (Chapter Two)

Annual numbers of fishing licenses sold in the country is reported by Sportvisserij Nederland (Royal Dutch Angling Association). This data was utilized as proxy data for the number of people interested in or utilizing fishing services. We compared reported regional numbers from 2016-2020 to trace shifts in trends. The data, distinguished by Dutch municipality, is presented as a figure.

3.3 Google trend data (Chapter Two)

Google trend data was used as proxy information regarding public interests in aquatic ecosystem services. Data regarding public interest in swimming locations was searched using the search term "zwemmen buiten" (English translation: "swimming outside") from 2016 to 2020. This data search occurred on 4 October 2021.

Google search trends for national park locations was used as a proxy dataset for human demand in shoreline walking. Trend data was gathered by using the park names as search terms. These six national parks were De Alde Feanen, De Biesborch, De Groote Peel, Dwingelderveld, Lauwersmeer and Weerribben-Wieden. These parks were chosen due to their inclusion of lakes or wetland areas within the management area, thus facilitating water-related ecosystem service provisioning (such as shoreline walking). Data was gathered from searched that occurred from 2016 to 2020. This data search occurred on 3 June 2021.

3.4 Online surveys

3.4.1 Online feedback survey (Chapter Three)

Anonymous feedback related to the perceived usefulness of the Flipping Lakes game was collected at an international freshwater-based conference. During this conference, there were opportunities for scientists, students and local lake managers to play moderated sessions of Flipping Lakes. Game participants and observers were given the option to provide anonymous feedback on the game, specifically on its usefulness for communication, education, and public outreach purposes. These responses were gathered through a survey form on a laptop belonging to one of the game moderators.

3.4.2 Self-assessment survey (Chapter Three)

Flipping Lakes was applied in an academic setting to assist with teaching concepts of freshwater science and management. During an Aquatic ecology course for bachelor students, the authors measured perceived comprehension of select lake science concepts by having students self-score their familiarity of the concepts on a scale from 0 (not familiar) to 10 (expert) prior to playing the game. Each student re-scored their familiarity of the same concepts after playing the game two to three times in groups of 4 students under the supervision of a game moderator. The scoring was carried out anonymously on a standardized scoring sheet which was printed on both sides, guaranteeing that participant results remained paired. Students provided permission to use the data for scientific publication through completion of an online survey form.

3.4.3 Online survey for collecting lake management perspectives (Chapter Four)

A 23-question online survey collated an overview of lake management perspectives regarding the application of science within management and how scientists can become effective collaborators. Acknowledgment of the data privacy statement (question 1) and participant demographic information (questions 2-6).

The survey aimed to attain an understanding four aspects of lake managers' perspectives. Questions 7-9 inquired about challenges affecting ecosystems, the ecosystem services used by the public and the management duties. Questions 10-12 inquired about how scientific information is currently being applied to management decision-making and what is the preferred method for applying scientific insights. Question 16-21 inquired about the current and preferred role of scientists in management-related discussions. Questions 14-15 and 22-23 inquired about manager suggestions to improve knowledge-sharing and communications across sectors.

Surveys were distributed through social media and through email invitation. The survey was accessible through the Surveymonkey platform from June to October 2020. Responses were quality controlled by removing incomplete responses from the database. To allow for regional comparisons, the responses were grouped with the United States of America and Canada combined into North America and Europe as the European Union. Weighing the number of responses within the regional categorization supported the direct comparison of manager perspectives between the North American and the European groups. Assessment of the responses from single choice, multiple choice and open-ended questions was conducted through descriptive analysis and using *ggplot2*.

3.5 Informal feedback (Chapter Three)

Flipping Lakes was introduced to professional water managers, master's students, university administration and the general public at other events. During these settings, the game was introduced as a tool to assist with communicating the needs of each group. For example, the game was set-up to simulate nearby water systems and to discuss theoretical management options with the professional water managers.

With the Masters students, the game was introduced in an introductory aquatic ecology course. This game was used to illustrate concepts to the students, which were primarily from the disciplines of civil engineering and microbial ecology. The game was also used at the end of the course to review the course material.

With the university administration staff and the general public, the game was used as a hands-on tool to introduce concepts of lake science and management. The visual nature of the game facilitated discussions about the various gameboard and game pieces. These games were moderated to assist with guiding gameplay and explaining the underlying concepts.

3.6 Semi-structured interviews (Chapter Four)

Nine semi-structured interviews were conducted with European managers responsible, fully or in part, for the implementation of the Water Framework Directive within their management jurisdiction. The interview questions related to 1) the challenges affecting the water systems within the organization's jurisdiction, 2) pressures and state of the water management area both presently and historically, 3) the creation and implementation process for the Water Framework Directive's Programme of Measures and 4) public involvement during the management process. Responses were used to supplement the findings from the online survey.

Interviews were held between September 2018 and May 2019, were conducted either in-person or through teleconference and lasted between one to two and a half hours. The interviewed water managers were associated with seven designated water authority organizations (five from the Netherlands, one from Spain, one from the United Kingdom) and two collaborator organizations (one from Spain, one from the United Kingdom). Interviews were recorded with consent of the interviewed party in order to conduct a thematic content analysis on the qualitative responses.

4. Data analyses

4.1 Chapter One

Linear mixed-effect models ("LME") analyzed the effects of our experimental treatments on the phytoplankton and nutrients. Shapiro Wilk tests checked data normality. If normality assumptions were violated, data was transformed through a logarithm, square root or reciprocal transformation. Breusch Pagan tests checked data heteroscedasticity and a weighted linear mixed-effect model was applied if necessary.

Principal response curve analysis ("PRC") was applied on multiple parameters to determine the system responses of the four different treatments over time and the weights of different parameters. Microcosms with the 18 ºC temperature treatment and without the precipitation simulation that were designated as the reference (baseline) to compare other microcosm treatments against. Data were standardized prior to the PRC analyses. All statistical analyses were performed in R with the packages *lubridate*, *ggplot2*, *nlme* and *vegan*.

4.2 Chapter Two

Visualization of the trends in searches for bathing waters and the comparison of the pre-pandemic data to the pandemic period was done using a LOESS smoothing function and the Wilcoxon signed rank test (R package *ggplot2*). The same method was applied to Google trend data for the national park search trends.

4.3 Chapter Three

Student scores from the bachelor course was analyzed using a paired Two-sample Fisher-Pitman permutation test (R package *coin*, Hothorn et al., 2019). Analysis of the results was conducted both by grouping all the lake concepts together and by looking at each of the concepts separately. The scores (x-axis) range between 0 (not familiar with the concept) to 10 (expert on the concept) and the y-axis gives the cumulative probability density (fraction of participants) based on the kernel density estimation method.

4.4 Chapter Four

Complete survey responses from the North America (n=47, “NA”) and Europe (n=15, “EU”) regional groups were compared for similarities and differences. All survey data was expressed as percentages to illustrate how many respondents from the respective regional groups selected the survey answer option. Responses were visualized using R package *ggplot2*.

Results

Chapter One - Stressors in a bottle: a microcosm study on phytoplankton assemblage response to extreme precipitation events under climate warming

Armstrong, M., Zhan, Q., Munthali, E., Jin, H., Teurlincx, S., Peters, P., Lürling, M., and de Senerpont Domis, L.N. (2023). Stressors in a bottle: a microcosm study on phytoplankton assemblage response to extreme precipitation events under climate warming, DOI: 10.1111/fwb.14109

1. Introduction

As sentinels within catchments, lakes can be particularly susceptible to climate change (Adrian et al., 2009; Stelzer et al., 2022). Along with shifts in the average climate, this also includes the increasing intensity and frequency of extreme climatic events ("ECEs"). While the implications of ECEs and long-term changes in average climate have been assessed in laboratory settings (e.g. microcosms; (Bergkemper et al., 2018), controlled environments (e.g. mesocosms; Richardson et al., 2019) and from observation data (e.g. modeling; Jöhnk et al., 2008), there are knowledge gaps on how different aspects of climate change interact and how these multiple climatic pressures will affect lakes. Understanding the biotic and abiotic pathways in which these compound pressures occur in combination with prolonged anthropogenic-driven stressors has been highlighted as a critical knowledge gap in the recent IPCC report (2022). Our study addresses this gap through analyzing the impact of an extreme precipitation event in conjunction with temperature rise on phytoplankton performance in a controlled setting mimicking northwestern European climate scenarios, as regional projections anticipate increases in extreme precipitation events (Madsen et al., 2014) and extreme summer heatwaves (McGregor et al., 2005; Woolway et al., 2021). As outlined by the Royal Dutch Meteorological Institute, an increase in higher intensity precipitation events during summer will track with higher temperatures (Klein Tank & Lenderink, 2009), thus supporting the potential of multiple extreme climatic events occurring simultaneously and necessitating research studying the potential effects.

1.1 Abiotic responses

Changes to lake chemical processes as a consequence of climatic stressors have the potential to instigate ecosystem disruptions (Calderó-Pascual et al., 2020). Between extreme precipitation and warming events, there can be abiotic ramifications such as nutrient loading, turbidity and water temperature change. The positive or negative outcomes of the stressors are dependent upon the local situation, such as regional location, antecedent lake conditions, the hydromorphology, time of year and event severity among other factors. Occurrences of extreme precipitation can lead to increased runoff (Jennings et al., 2012), such that runoff from a single extreme precipitation event could account for a significant portion of the total annual nutrient loading (Zwart et al., 2017). Conversely, precipitation events could cause nutrient depletion from flushing of a system (Ho & Michalak, 2020) or dilution (Cobbaert et al., 2014). Likewise, turbidity could be altered from the re-suspension of *in situ* sediments (Kasprzak et al., 2017), in turn decreasing water transparency (Kasprzak et al., 2017) and light availability (Stockwell et al., 2020). Warming of water systems from climatic-influenced events can also impact abiotic aspects of systems, as evidenced through strengthening stratification in water columns and the subsequent effect this has on biogeochemical processes (De Senerpont Domis et al., 2013; Velthuis et al., 2017; Wagner & Adrian, 2009).

1.2 Biotic responses

Phytoplankton biomass can be positively or negatively affected by the occurrence of climatic events depending upon how these events manifest in the water system. For example, extreme precipitation can instigate phytoplankton growth with nutrient loading from runoff (De Senerpont Domis et al., 2013) or thermal pollution from impervious surfaces increasing the temperature of runoff water (Van Buren et al. 2000). Heatwaves likewise can contribute to phytoplankton growth with warming the water to temperatures more favorable for some species such as cyanobacteria, particularly when warming is also paired with a nutrient-rich environment

(Lürling et al., 2018). However, the occurrence of climatic events can also negatively affect phytoplankton biomass through the abiotic changes. For example, phytoplankton can be placed at a disadvantage when nutrients become diluted (Cobbaert et al., 2014), lower temperatures create unsuitable conditions (Wood et al., 2017) and phytoplankton are flushed from the system (Stockwell et al., 2020). Shifts in light availability caused by alterations of turbidity (Bergström & Karlsson, 2019; Perga et al., 2018) can also select for phytoplankton species with a competitive advantage (Ekvall et al., 2013; Feuchtmayr et al., 2019), such as for cyanobacteria with the capacity for vertical movement (Walsby et al., 1991). Species that are outcompeted as a result of turbidity as well as temperature, nutrients and flushing, may lead to a decrease in overall phytoplankton biomass as well as shifts in community composition favoring harmful cyanobacterial blooms.

1.3 Multiple stressors

Pulse-press disturbance categorization (Bender et al., 1984) can be applied to climatic stressors with short, intense extreme events being "pulse" disturbances and prolonged climatic pressures being "press" disturbances (Harris et al., 2018). The combination of these two stressors can have notable implications on biological communities such as shifts in community richness and species dominance (e.g. Graham & Vinebrooke, 2009; Harris et al., 2018). At present, few studies have focused on the combined effect of an extreme event (pulse disturbance) and mean climate change (press disturbance) on phytoplankton (e.g. Bergkemper et al., 2018; Richardson et al., 2019), particularly with combined stressors of allochthonous materials and temperature (Graham and Vinebrooke, 2009). Elucidating the mechanisms behind interactive effects of climatic stressors requires experiments in a controlled setting.

1.4 Experiment

We carried out a microcosm study with three phytoplankton populations (i.e. cyanobacteria, diatom and green algae), mimicking the primary food-web base of a typical eutrophic Dutch lake under two climate scenarios (ambient summer water temperature and +6ºC summer water temperature). Half of the microcosms were also exposed to an extreme precipitation event. We tested two hypotheses (H1 and H2) with the full-factorial treatment design. H1: under eutrophic conditions, the higher water temperature microcosms will support a larger phytoplankton biomass than the ambient temperatures. Previous studies have illustrated the implications of heatwaves on the proliferations of algal blooms (e.g. Johnk et al., 2008; Urrutia-Cordero et al., 2020), particularly with the presence of heat-adapted species such as cyanobacteria (e.g. Filiz et al., 2020). H2: upon exposure to the runoff event, we predict that there will be a larger difference in productivity in the warmer versus ambient climate treatments, thus creating more competitive advantages for cyanobacteria. Such productivity can result when higher temperatures instigate more phytoplankton primary production activity and, in combination with access to readily available nutrients, can support significant growth (Paerl & Paul, 2012). This is in line with studies regarding the effect of eutrophication in supporting phytoplankton proliferation (e.g. Hansson et al., 2013; Schindler, 1978).

2. Methods and materials

2.1 Experimental design

We carried out a full-factorial microcosm experiment where an artificial phytoplankton assemblage was exposed to an ambient and regional warming scenario for a period of 23 days. Both ambient (18ºC) and warm (24ºC) microcosms were exposed to a runoff event on Day (D)13 to test whether the microcosm response to an extreme precipitation event was amplified or controlled by temperature. Each treatment had six replicates, resulting in a total of 24 microcosms (six replicates x two temperature treatments x absence/presence of runoff event). Each microcosm was inoculated with a phytoplankton assemblage consisting of cyanobacterium *Anabaena flos-aquae* (CCAP 1446/1C), green alga *Chlorella vulgaris* (UTEX 26) and diatom *Synedra sp.* (from a 2009 field isolate from Lake Maarsseveen, The Netherlands, 52°08'32.2" N 005°04'53.7" E). These species were chosen for the simplified assemblage as they are common in eutrophic systems throughout The Netherlands and represent the dominant cyanobacteria, green algae and diatoms of our reference Omloop Lake (The Netherlands, 51.79242 N, 4.95114 E). Additionally, these three species exhibit differing traits and preferences that can assist in testing the implications that the experimental treatments had on their competitive ability. The microcosms were sampled at a 2-3 day interval, with six samplings occurring before the D13 runoff event and five happening after.

2.2 Reference Omloop Lake

Our experimental phytoplankton species and their relative abundance, the temperature treatments and the precipitation runoff simulation were based on the conditions present in Omloop Lake, which is a hydrologically isolated, moderately deep (6.8m) and eutrophic lake system located in southwest Netherlands (51.79242 N, 4.95114 E). The summer conditions of this lake are representative of many of the anthropogenically-created water bodies in the country. In line with regional trends, land-use induced nutrient enrichment is leading to the eutrophic state of water bodies and an abundance of cyanobacteria.

2.3 Microcosm design

The microcosms consisted of 10-L Nalgene containers (Nalgene, Rochester, United States of America) filled with 3.5L autoclaved COMBO medium (Kilham et al., 1998.; Supplement 1, Table S1). Algal trace element solution stocks for $Na_2EDTA{\cdot}H_2O$ and $FeCl_3{\cdot}H_2O$ were stored and added separately to the Nalgene microcosms to avoid crystallization. At the start of the experiment (D0) the microcosms were inoculated with 540 mL of the algae stock. The introduced biomass was composed of 24% *Anabaena flos-aquae*, 50% *Chlorella vulgaris* and 26% *Synedra sp*. This biomass distribution was chosen to emulate a typical eutrophic Dutch lake system under summer conditions with green algae dominance following the phytoplankton seasonal succession (De Senerpont Domis et al., 2007). Incident light was set at 24.91 ± 4.74 μmol photons m^{-2} s^{-1} integrated over PAR (TL Osram 18w/840, Berlin, Germany) programmed for 16h:8h, light:dark photoperiod (Theben selecta 170 top 2 digital astronomical switch set, Haigerloch, Germany). This light intensity is around the critical light intensity of the phytoplankton types involved (e.g. Huang et al., 2018; Shi et al., 2015; Shu et al., 2012). The microcosms were closed off with a silicone stopper to prevent contamination by air and evaporation losses. This stopper contained an air vent with a filter and a tubing system through which an air flow was administered to prevent oxygen (O_2) depletion and to create a subtle mixing of the water column. Microcosm water columns were homogenized three times per week through manual perturbation to prevent phytoplankton adherence to surfaces.

2.4 Treatment scenarios

2.4.1 Temperature

Water temperature scenarios were based on average and extreme summer temperatures using hourly air temperature data records (1951-2017) of the Royal Dutch Meteorological Institute's de Bilt weather station. Air temperatures were converted to water temperatures with the Dutch surface water model developed by Mooij et al. (2008), yielding 18ºC and 24ºC for ambient and warm scenarios, respectively. Temperature treatments were administered through water baths containing a heating element (EHEIM 3619 300W heater, Deizisau, Germany) and an underwater pump (EHEIM compactON 1000, Deizisau, Germany). Water temperature was controlled with a custom climate control system (SpecView, Uckfield, United Kingdom) at +/- 0.5ºC.

2.4.2 Precipitation

The extreme precipitation-induced runoff event was based on daily precipitation values from de Bilt weather station's 1906-2017 summer precipitation records. To attain a realistic scenario of soil runoff volumes we performed rainfall simulations with the Wageningen University + Research Soil Physics and Land Management Group rainfall simulator (Lassu et al., 2015; Supplement 2). Soil samples from the shore of Omloop Lake were taken to simulate particulate material in overland runoff. Based on these rainfall simulations, precipitation treatments were represented in the microcosms through introduction of a soil runoff solution (2.9g soil dissolved in 600mL demi water, equal to approximately 15% microcosm volume dilution) to the extreme precipitation-assigned microcosms. To mimic the increased water volume that takes place after intense precipitation for lakes with no outflow, the total volume of the precipitation-treated microcosms increased to approximately 4.6L in the 10-L containers, and maintained the higher volume (as compared to the non-precipitation-treated microcosms) for the remainder of the experiment. As such, dilution of dissolved nutrient concentrations in the microcosms occurred with the application of the rainfall simulation resulting from the added runoff increasing the total microcosm volume. During the experiment, removed sample volumes were replaced with equivalent amounts of COMBO medium following every sampling (approximate 2% dilution per sampling event). The nutrient composition in the runoff was 125mg/L particulate carbon, 12mg/L particulate nitrogen (N) and approximately 0.08mg/L mobile phosphorus (P), of which 0.004mg/L was the readily available P fraction, 0.06mg/L was the redox sensitive P fraction and 0.01mg/L was the organic P fraction as was determined through an adjusted version of the psenner soil analysis (Cavalcante et al., 2018; for details on measurements see Supplement 3, Table S3). Carbon (C), N and P were measured as these values will provide insight into potential macronutrient limitations, whereas other nutrients such as silica and iron were not measured as they are perceived to be sufficiently provided through the quantity and frequency of COMBO medium that was added into the microcosms (Supplement 1, Table S1). The runoff event was applied to microcosms on D13 of the experiment.

2.5 Sample analysis

2.5.1 Sample collection

To account for vertical heterogeneity in phytoplankton abundance, samples were collected from microcosms using sampling tubes. During experiment D0-12, approximately 170mL of sample volume was collected from each microcosm. After D13, microcosms treated with runoff had approximately 230mL collected during sampling. All sampled volumes were replaced with equivalent amounts of COMBO medium to compensate for the loss in water as well as nutrients.

2.5.2 Phytoplankton

The microcosm phytoplankton assemblage composition was quantified during each sampling event using a PhytoPAM fluorometer (WALZ, Effeltrich, Germany). This method was used as it has been considered more reliable than microscopic counting methods (Lürling et al., 2018). Before the onset of the experiment, we conducted a regression analysis of PhytoPAM measurements versus Coulter counter (Beckman Coulter Nederland BV, Woerden, the Netherlands) counts of the individual phytoplankton cultures which yielded high agreement between these two measurements (*Anabaena flos-aquae* $R^2 = 0.96$, *Chlorella vulgaris* $R^2 = 0.97$, *Synedra* $R^2 = 0.94$, see Supplement 4, Figure S4A-C). Calculated dilution corrected concentrations are shown for Total Chlorophyll-a (Chl-a) in Supplement 5, Figure S5.1.

2.5.3 Abiotic

In order to determine dissolved and particulate nutrient fractions, samples were filtered with Aquadest-washed glass microfiber filters (Whatman GF/F, Maidstone, United Kingdom). Filters were dried for 24h at 60°C before being stored in a desiccator. Filters for particulate P were incinerated at 550°C for 20min then autoclaved with a 2% potassium persulfate solution at 121°C for 30min Resulting solutions were analyzed for P concentrations with a Quaatro segmented flow analyzer (Seal Analytical, Beun de Ronde, the Netherlands). Particulate C and N fractions were determined from filter samples with a FLASH 2000 organic elemental analyzer (Interscience B.V., Breda, the Netherlands). Filtrate samples were stored at -20ºC until run through an ASI-L Auto Sampler (Shimadzu, Kyoto, Japan). Soluble reactive P (SRP, referred to as dissolved P), total oxidized N, nitrite, nitrate and ammonium concentration were quantified with a Quaatro segmented flow analyzer. Dissolved organic C and dissolved inorganic C were measured weekly in a TOC-L Total Organic Carbon Analyzer (Shimadzu, Kyoto, Japan). Phosphorus and N were calculated through summation of the measured dissolved and particulate nutrient fractions. Calculated dilution concentrations are shown for dissolved P and dissolved N in Supplement 5, Figures S5.2-3.

Prior to sampling, a WTW Multi 350i Field Meter (WTW, Weilheim, Germany) measured water temperature, pH and dissolved O of the microcosms. Turbidity was measured weekly with a WTW Turb430IR Meter (WTW, Weilheim, Germany; Supplement 7).

2.6 Statistics

Linear mixed-effect models ("LME"; Lindstrom & Bates, 1988) were used to analyze the effects of our experimental treatments on the phytoplankton and nutrients. Precipitation treatment runoff (RUNOFF), temperature (TEMP) and time (TIME) were integrated as fixed factors. Data were analyzed for the full time period, as well as for the before and after runoff periods separately. For the latter, we divided the dataset into a before runoff period (0–12 days), where only temperature and time effects were evaluated, and a post runoff period (14–23 days), where the effect of the precipitation treatments was also assessed. We opted to present and discuss the analyses of the dataset in only two time periods as, upon the application of the runoff treatment, the microcosms exhibited contrasting trajectories relative to before runoff periods (i.e. changed slope and intercept). To account for the variation in initial states among microcosms for both before runoff and after runoff periods, we included the individual microcosms as a random term in the LME model. A metric called intraclass correlation (ICC) was used for evaluation of the significance of random effects. The ICC, by calculating the ratio of between-cluster variance to total variance, can be helpful in determining whether random effects are needed (Theobald 2018). For completeness, we document both the analysis of the full time period as well as the separate analyses of the two time periods (in Supplement 6, Tables S6.1-10). The Shapiro-Wilk test (Ghasemi & Zahediasl, 2012) was used to check for normality. If normality assumptions were violated, we transformed the data through a logarithm, square root or reciprocal transformation. If transformed data still did not meet the assumption of normality, we chose to show the model outcome on the untransformed data but associated the p-values with a more conservative probability cut-off (i.e., only factors with very small p-value were considered significant; Fowler-Walker & Connell, 2002). In addition, we used the Breusch-Pagan test (Waldman, 1983) to check for data heteroscedasticity and a weighted linear mixed-effect model was applied if necessary. Additionally, the interaction term was calculated for the total Chl-a, individual phytoplankton species, P and N LME models to evaluate the potential interactive effects of multiple stressors (Supplement 6, Tables S6.1-10).

Principal response curve analysis ("PRC"; Van den Brink & Braak, 1999), a multivariate statistical method, was carried out on multiple parameters to determine the system responses of the four different treatments over time and the weights of different parameters. In our study, we set the ambient temperature (18ºC) and non-runoff-treated microcosms as the reference (baseline) to compare other treatments against. Data were standardized prior to the PRC analyses. All statistical analyses in this study were performed in R (Team, 2019) with the packages *lubridate* (Grolemond & Wickman, 2011), *ggplot2* (Villanueva & Chen, 2019), *nlme* (Pinheiro et al., 2019) and *vegan* (Oksanen et al., 2019).

3. Results

3.1 Biotic response

The runoff and temperature effects were assessed for the total phytoplankton biomass (Figure 1A) and for the three species individually (Figures 1C-E) through a LME model. Temperature had a significant positive effect on total Chl-a concentrations throughout the duration of the experiment ($F_{1,118}$ = 5.09, p <0.05, D0-12, TEMPxTIME; $F_{1,92}$ = 7.35, p <0.05, D14-23, TEMPxTIME). The runoff event resulted in a significant lowering of total phytoplankton biomass ($F_{1,92}$ = 4.55, p <0.05, D14-23, RUNOFFxTIME; Figure 1A). However, there was no significant interaction detected between both climatic events ($F_{1,92}$ = 0.02, p = 0.89, D14-23, TEMPxRUNOFFxTIME). To explore the dilution aspect of the runoff event, we calculated changes in total Chl-a of the non-runoff event exposed treatments (18ºC & 24ºC) as a result of dilutions. These graphs are provided in Supplement 5, Figure S5.1A-B.

The dynamics of phytoplankton biomass in response to experimental treatments are shown in principal response curves (PRC, Figure 1B), with the weight of each species indicating their influence on the overall dynamics. The cyanobacterium *Anabaena flos-aquae*, and to a lesser extent the diatom *Synedra*, showed opposing influences on the principal responses in comparison with the green alga *Chlorella vulgaris*. This differential response becomes apparent only at D6, with higher temperatures resulting in higher cyanobacteria ($F_{1,118}$ = 116.66, p <0.0001, D0-12, TEMPxTIME; Figure 1C) and diatom concentrations ($F_{1,22}$ = 25.96, p <0.0001, days 0-12, TEMP; Figure 1E) as well as lower green algal concentrations ($F_{1,118}$ = 41.92, p <0.0001, D0-12, TEMPxTIME; Figure 1D).

Following the runoff event on D13, recipient microcosms had a short-term but non-significant decline in cyanobacteria and diatom biomass ($F_{1.92}$ = 1.74, p = 0.19, day 14-23, RUNOFFxTIME; $F_{1.92}$ = 1.79, p = 0.18, D14-23, RUNOFFxTIME), and a non-significant increase in green algal biomass ($F_{1.92}$ = 3.10, p = 0.08, D14-23, RUNOFFxTIME). Within the warmer microcosms, such a decline in biomass occurred on D14 and recovered to levels equivalent to non-runoff-treated microcosms by D16 (Figure 1B). Ambient temperature microcosms had a delayed effect with the decline visible starting at D18 and reaching biomass levels equivalent to the non-runoff-treated microcosms on D23 (Figure 1B). Temperature did not amplify or control the response of the phytoplankton assemblage to the runoff event and remained significant in determining cyanobacterial ($F_{1,92} = 5.56$, $p < 0.05$, D14-23, TEMPxTIME; Figure 1C), diatom ($F_{1,20} = 4.62$, $p < 0.05$, D14-23, TEMP; Figure 1E) and green algal biomass ($F_{1,92} = 146.85$, $p < 0.0001$, D14-23, TEMPxTIME; Figure 1D). The runoff effect (RUNOFF or RUNOFFxTIME) was not significant for any of the individual species.

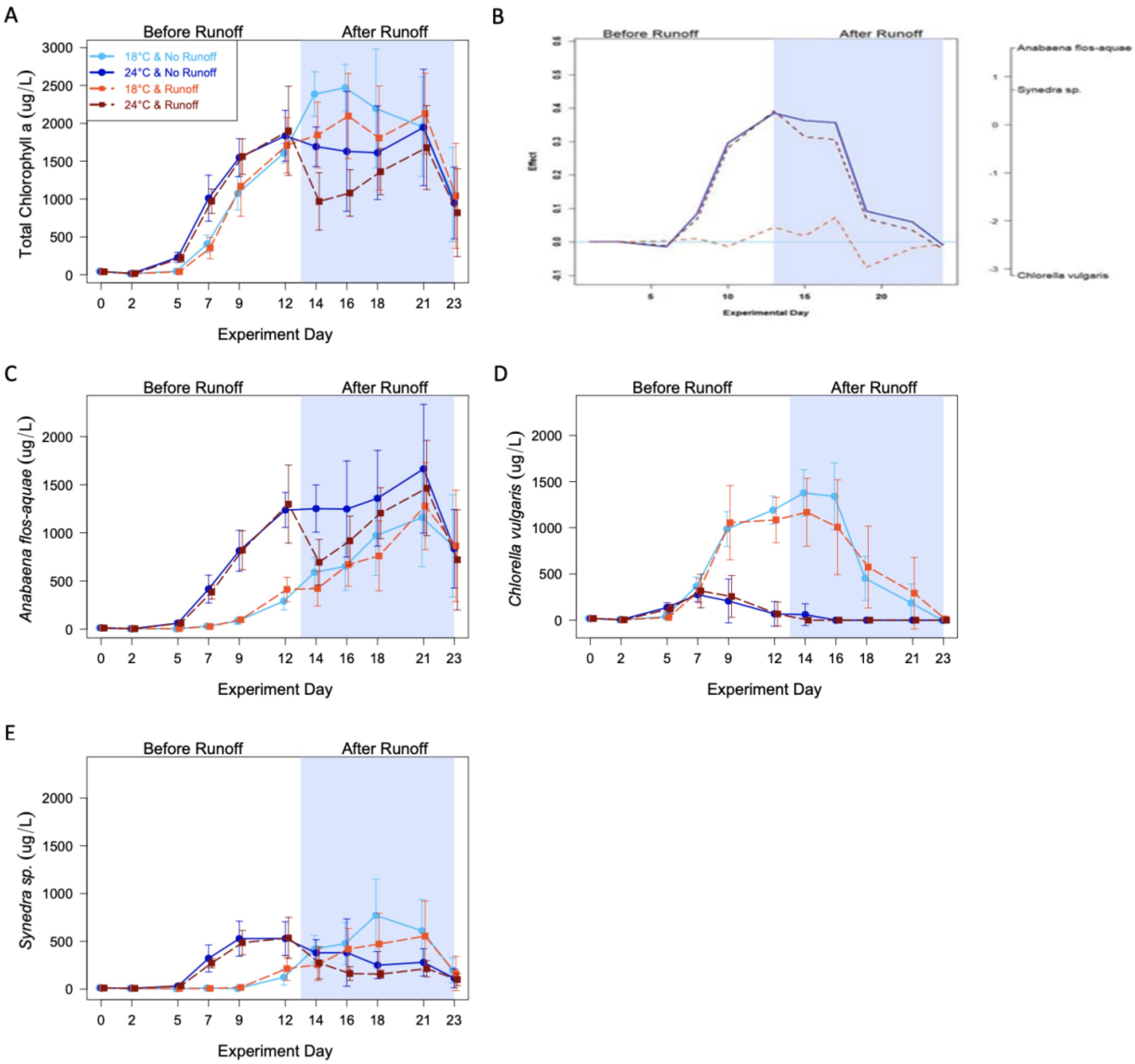


FIGURE 1: Overall phytoplankton biomass (chlorophyll-a concentration) presented by microcosm treatment (**A**) and with principal response curves ("PRC") of phytoplankton species, as expressed by coefficient effects for the control and each experimental treatment (**B**). The PRC figure visualizes the multivariate response of the microcosm community (expressed in canonical regression coefficient Cdt, left y-axis) over time (x-axis) to the different treatments relative to the control (the baseline) and to what extent this response was influenced by the individual

phytoplankton species concentrations (expressed in the species weight bk, right y-axis). A positive weight on the right y-axis for a specific parameter indicates that this parameter is positively correlated with the observed patterns. Conversely, a negative weight on the right y-axis indicates that a specific parameter is negatively related with the observed patterns. Individual algal species concentrations measured with PhytoPAM of chlorophyll-a for each experimental treatment and control treatment are presented for *Anabaena flos-aquae* (**C**), *Chlorella vulgaris* (**D**) and *Synedra sp.* (**E**). Lines: light blue solid line represents ambient temperature (18ºC) & no runoff, the dark blue solid line represents warm temperature (24ºC) & no runoff, the light red dashed line represents ambient temperature (18ºC) & runoff, and the dark red dashed line represents warm temperature (24ºC) & runoff.

3.2 Nutrients

3.2.1 Sum of particulate and dissolved nutrients

The sum of particulate and dissolved P concentrations (particulate P + PSRP) in warmer microcosms was significantly higher than that in ambient microcosms during the first half of the experiment. Distinct differences between the warmer and ambient microcosms are visible on D12 of the experiment. This trend, however, was lost after the application of the runoff event ($F_{1.92}$ =1.86, p>0.05, D14-23, TEMPxTIME). Following the runoff event, there was a nearly significant effect of precipitation on the particulate and dissolved P content of the microcosms ($F_{1,92}$ = 3.43, p=0.07, D14-23, RUNOFFxTIME). Throughout the duration of the experiment, temperature had a significant positive effect on particulate and dissolved N concentrations (particulate N + nitrite + nitrate + ammonia; $F_{1,22}$ = 11.34, p<0.005, D0-12, TEMP; $F_{1,20}$ = 5.55, p<0.05, days 14-23, TEMP; Figure 2B).

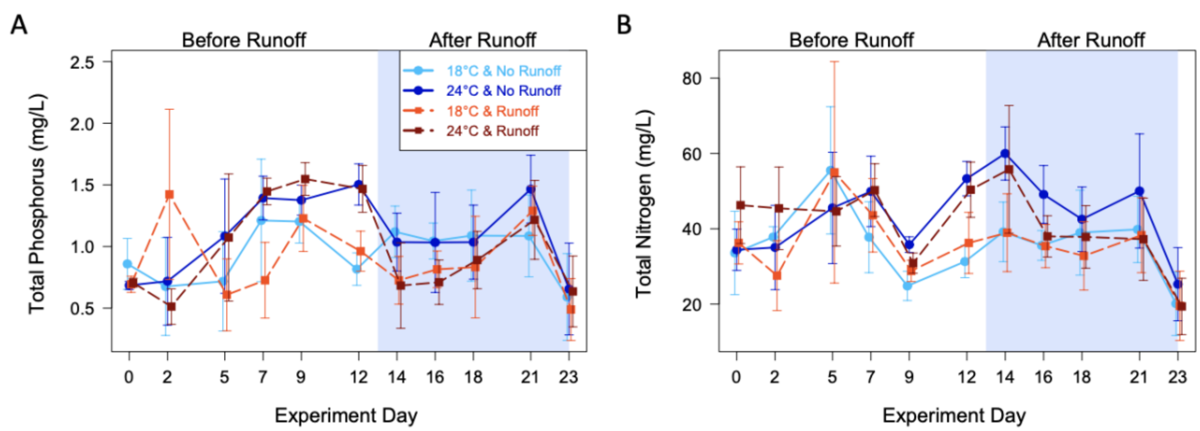


FIGURE 2: Total phosphate (**A**) and nitrogen (**B**) by treatments. Lines: light blue solid line represents ambient temperature (18ºC) & no runoff, the dark blue solid line represents warm temperature (24ºC) & no runoff, the light red dashed line represents ambient temperature (18ºC) & runoff, and the dark red dashed line represents warm temperature (24ºC) & runoff.

3.2.2 Dissolved and seston nutrients

Initial average dissolved P concentrations were recorded at 0.66mg/L (D1, Figure 3A). Microcosms maintained high concentration levels until D7, after which there was a decline. The change in dissolved P levels closely coincides with the increase of total Chl-a across all microcosm treatments (Figure 1A). Following D12, dissolved P remained at near non-detectable levels regardless of the treatment ($F_{1,92}$ = 1.32, p >0.05, D14-23, TEMPxTIME; $F_{1.92}$ = 2.88, p >0.05, D14-23, RUNOFFxTIME). To explore the dilution aspect of the runoff event, we calculated changes in dissolved P of the non-runoff event exposed treatments (18ºC & 24ºC) due to dilutions. These graphs are provided in Supplement 5, Figure S5.2A-B.

Dissolved N concentrations (nitrate + nitrite + ammonium) had a similar overall decrease in concentration (Figure 3B) with no temperature effect detected ($F_{1.118}$ = 0.03, p >0.05, D0-12, TEMPxTIME; $F_{1.92}$ = 0.33, p >0.05, D14-23, TEMPxTIME). However, over D9-14 there was a brief increasing trend for all microcosms, wherein the warmer microcosms displayed sharper concentration increases. In contrast to dissolved P, the dissolved N did not decrease to near non-detectable levels. During the post-runoff period, the precipitation treatment also had a significant effect on dissolved N concentrations, as seen on D14 ($F_{1,92}$ = 4.71, p <0.05, D14-23, RUNOFFxTIME). To explore the dilution aspect of the runoff event, we calculated changes in dissolved N concentrations of the non-runoff event exposed treatments (18ºC & 24ºC) as a result of dilutions. These graphs are provided in Supplement 5, Figure S5.3A-B.

Particulate P increased before the runoff event, with the warm microcosms increasing more rapidly than the ambient temperature microcosms ($F_{1,118}$ = 26.98, p <0.0001, D0-12, TEMPxTIME; Fig 3C). However, this significant interaction disappeared following the runoff event ($F_{1.92}$ = 1.27, p >0.05, D14-23, TEMPxTIME). Despite the introductions of sediment-associated nutrients, exposure to the runoff event had a non-significant impact on the P concentrations ($F_{1,20}$ = 4.25, p = 0.05, D14-23, RUNOFF; Figure 3C). Particulate N showed similar responses with the higher rates of increase in the warmer microcosms versus the ambient temperature microcosms ($F_{1,118}$ = 20.96, p <0.0001, D0-12, TEMPxTIME; Figure 3D) before disappearing upon exposure to the runoff event ($F_{1.92}$ = 0.05, p >0.05, D14-23, TEMPxTIME).

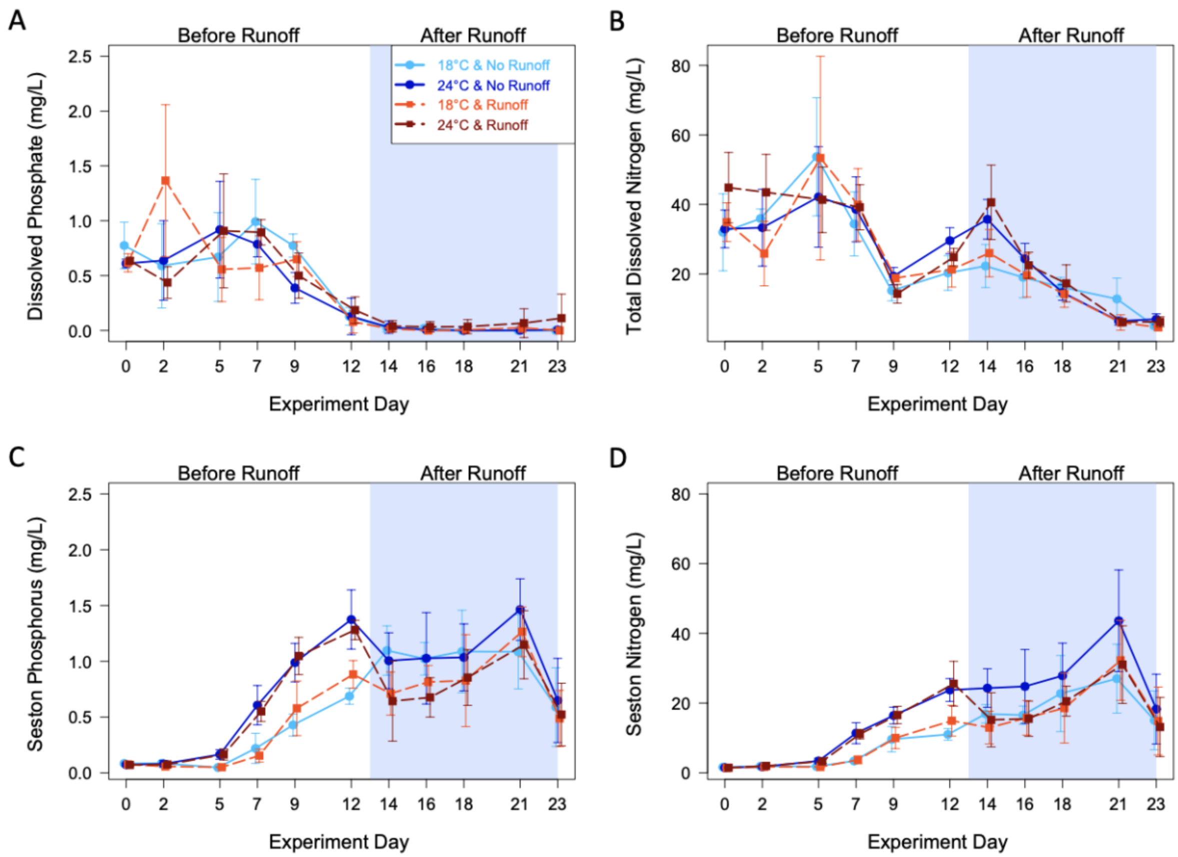


FIGURE 3: Experimental treatments and control treatment are presented for dissolved phosphorus (**A**), dissolved nitrogen (**B**), seston phosphorus (**C**) and seston nitrogen (**D**). Lines: light blue solid line represents ambient temperature (18ºC) & no runoff, the dark blue solid line represents warm temperature (24ºC) & no runoff, the light red dashed line represents ambient temperature (18ºC) & runoff, and the dark red dashed line represents warm temperature (24ºC) & runoff.

4. Discussion

We examined the implications of coinciding climatic stressors on a phytoplankton assemblage within a full-factorial microcosm experiment design. Our study aim was to analyze the effects of runoff and temperature on phytoplankton under typical northwestern European summer conditions. For this, the microcosms emulated a eutrophic and hydrologically-isolated water system, which is common for deeper lakes throughout the Rhine and Meuse delta (Seelen et al., 2021). Regional temperature and precipitation data were utilized to devise the summer ambient and extreme treatments. Within this design, a coinciding chronic press stressor and short-term pulse stressor were administered through a warming event and a precipitation runoff event, respectively. Our study showed that the individual temperature treatments had a more significant effect on the phytoplankton assemblage than the combined treatment. Specifically, this resulted in proliferation of cyanobacteria biomass, and to an extent of diatom biomass, in the warmer treatments and green algae biomass in the ambient treatments. The runoff event, however, had a transient effect on the phytoplankton dynamics with a short-lived decrease in Chl-a measured in the overall phytoplankton and the individual cyanobacteria in the higher temperature treatment. Based on these results, we here discuss the influence of press and pulse stressors in lake systems as well as suggestions for future studies.

4.1 Temperature treatment

In support of our first hypothesis, the observed phytoplankton dynamics highlighted the role of temperature in stimulating biomass growth, with the exception of the green alga *Chlorella vulgaris*. This species has been observed to have a range of temperatures for promoting growth. Under controlled conditions, *Chlorella vulgaris* has been observed to achieve high growth rates at 25-30ºC (Sharma et al., 2012), although growth has also been observed up to 35ºC (Lee et al., 1985). However, within our assemblage setting, *Chlorella vulgaris* was unable to outcompete *Anabaena flos-aquae* at the higher microcosm temperature. In comparison, our cyanobacterial species demonstrated the largest growth rate under warm conditions. Previous studies have demonstrated this relationship through laboratory experiments (e.g. Kosten et al., 2012), modelling (e.g. Elliott et al., 2005; Mooij et al., 2007) and observations (e.g. Konopka & Brock, 1978). Our results are congruent with growing concerns regarding how intensified warming could impact lake ecosystems, especially those in already eutrophic or degraded states. The dominance of cyanobacteria under the warming treatments, relative to the ambient treatments, can cause challenges as these species are capable of disrupting food web dynamics (e.g. Bartosiewicz et al., 2019) and causing health concerns with toxin production (Francy et al., 2016). Microcystin in particular has been a prominent toxin of concern in freshwater systems (Faassen & Lürling, 2013). Although our study incorporated measurements to evaluate microcystin concentrations, its production was considered absent in our microcosm study as toxin levels were undetectable. However, other cyanobacteria species within the phytoplankton community may be capable of producing toxins under similar experimental conditions (e.g. Lürling et al., 2017).

Additionally, the higher temperature treatment had a significant effect on the measured (dissolved + particulate) P fractions in the microcosms. A significant difference in P levels occurred in the time period before the application of the runoff simulation. As the microcosms were closed systems, the difference in P concentrations could not be accounted for owing to removal of P from the system. Aside from sampling events, the contents of the microcosms were not removed. We hypothesize that the ambient temperature instigated an increase in the quantity of colloidal P, which would thereby render the nutrient immeasurable in the dissolved and particulate nutrient analysis. We recognize, however, that not all fractions of P or of N were accounted for in the sample analysis. Therefore, in future, incorporating additional analyses of other nutrient fractions into the experimental set-up can further elucidate the mechanisms behind the significant difference in nutrient concentrations.

4.2 Precipitation runoff treatment

The impact of the runoff event on the phytoplankton was apparent through a significantly lower phytoplankton assemblage biomass, although this effect was not evident for the individual species. As precipitation runoff is capable of instigating a range of disparate effects within the recipient aquatic setting (e.g. Feuchtmayr et al., 2019; Kasprzak et al., 2017; Morabito et al., 2018), there could be a number of mechanisms behind the alteration in total Chl-a concentration in our experimental microcosms. On the one hand, the increase of the turbidity after the runoff event (Supplement 7, Figure S7) may have posed a light limitation for the phytoplankton. A visual, short-lived increase in suspended solids following the application of the runoff supports the role of turbidity within our microcosm setting. Continuous measurements of light levels within the water column could assist in further elucidation of the influence of such a runoff event in future experiments. On the other hand, the abrupt addition of 600mL soil runoff solution into the extreme precipitation-treated microcosms could also have caused a dilution effect. As demonstrated in previous studies, the influx of water from an extreme precipitation event can lead to a decreased biomass through system dilution (e.g. Wood et al., 2017).

The calculated dilution from the runoff event (Supplement 5, Figures S5.1A-B) illustrated a relatively small decrease in phytoplankton biomass. The approximation of the dilution aspect of the runoff event of dissolved nutrients (Figures S5.2A-B and S5.3A-B) indicates that the dilution aspect of the runoff event could at least partially be mitigated by the increased availability of nutrients upon runoff exposure. The increased availability in nutrients due to runoff, however, did not result in long-lasting effects as by the end of the experimental period, no difference could be observed between runoff exposed versus non-runoff exposed microcosms. The P fractionation of the runoff sediment showed that only 0.004mg/L was readily available P fraction, whereas the largest part of the potentially mobile P pool comprised the redox-sensitive (0.06mg/L) and organic P (0.01mg/L) fractions. Probably the relatively short post-runoff experimental period and the presence of O_2 through the experimental period (data not shown) impeded the accessibility of the redox-sensitive and organic P fraction for the phytoplankton. It is likely that the limited nutrients that were readily available (i.e., dissolved P) were rapidly taken up by the phytoplankton assemblage as dissolved P remained at near limiting levels, and dissolved N levels were only temporarily significantly elevated.

4.3 Multiple stressors in freshwaters

Contrary to our second hypothesis, temperature did not amplify or control the impact of runoff on the microcosms. In the second half of the experiment, both the temperature increase (24ºC) as well as exposure to a runoff seemed to reduce Chl-a concentrations relative to the control conditions (18ºC, no runoff). Whereas this effect was subtle but not significant for the runoff only treatment, it was significant for a short time period in both the 24ºC treatment (D14) as well as the combined treatment (D14 and D16). Following the classification of potential interaction types between multiple stressors by Piggot et al. (2015), the conditions wherein an interaction may occur include when two single stressor effects 1) oppose each other, 2) act in the same direction, 3) when both stressors have no effect individually and 4) when one single stressor has a significant effect and the other stressor does not have a significant effect. In our study during the period just after exposure to the runoff treatment (D14), simultaneous exposure to runoff and 24ºC temperature resulted in stronger negative impact on Chl-a biomass levels than the effect of the single stressors, thereby demonstrating a negative synergistic effect (based on a negative (24ºC)-neutral (runoff) interaction type) according to Piggot et al.'s classification. For the precipitation simulation, this could be due to the runoff treatment having mainly had a hydrological diluting effect rather than a biogeochemical effect. As for temperature, the 24ºC microcosms exhibited trends of *Anabaena* growth briefly leveling off, *Chlorella* crashing and *Synedra* having peaked around D14. In comparison, the phytoplankton in the 18ºC microcosms exhibited steady growth around the period of the runoff application. Regardless of the mechanism, the two treatments did not have the anticipated effect of increasing phytoplankton biomass.

Comparably designed microcosm experiments have found other effects when multiple climatic stressors were combined into one treatment; previous microcosm studies using heating and nutrient addition treatments have found that there was a positive effect on phytoplankton abundance when the treatments were individually applied, yet a lesser effect occurred when the two treatments were applied together (e.g. Richardson et al., 2019). A meta-analysis of multiple stressor freshwater studies by Jackson et al. (2016) indicated that multiple stressors predominantly (48%) had an antagonistic impact on the functional performance of freshwater ecosystems, rather than an synergistic (28%) or additive interaction (16%). This antagonistic interaction phenomenon in freshwater systems has been theorized to be rooted in these systems' potential to acclimate to pressures quickly as a result of environmental variability, specifically with co-adaptation in the systems dampening multiple stressor effects (Jackson et al., 2016). In future controlled system studies, particularly those with more complex food webs, these patterns of antagonistic or synergistic interactions may be more directly observed. Further, the upscaling of mechanistic findings such as those from this experiment can be tested.

4.4 Press and pulse stressors in freshwaters

In situations where press and pulse pressures are paired, the press stressors can be indicative of the overall effect. As witnessed in our study, the effects of temperature on the phytoplankton community eclipsed those of the runoff event in magnitude of change, effectively accounting for the majority of the significant effects. Similar press events have been noted to present a larger effect on lake systems as compared to coinciding pulse events. For instance, the coinciding long-term heatwave and the short-term storm events observed in Lough Feeagh during summer 2018 instigated different effects on the system. On a time-scale perspective, the implications of the heatwave persisted in the lake longer than those of the storm event (Calderó-Pascual et al., 2020).

However, pulse stressors also contribute to the cumulative effect of multiple stressors. By their nature, pulse stressors can stimulate intense responses in a system over a short period of time (Harris et al., 2018). The capacity of lakes to quickly mitigate a pulse stressor may provide an opportunity for the system to recover the pre-disturbance functions, but the shortening return period of these events can hamper the resilience of lakes. Further, lags or legacy effects from the pulse events can cause complications (Harris et al., 2018), such as mitigation measures not being implemented or the delayed effect coinciding with another stressor.

4.5 Caveats and future steps

We studied the combined effect of a climatic press and pulse stressor on an experimental phytoplankton assemblage. Over the course of the experiment, the microcosms exhibited significant effects resulting from the applied treatments. Of interest is that all of the microcosm assemblages exhibited a decline towards the end of the experimental period. We hypothesize that a limitation of resources, particularly of nutrients, became unsustainable and led to an observed decrease in total phytoplankton biomass levels following D21. Furthermore, the presented methods could be improved upon for evaluating assemblages. For instance, our approach of using PhytoPAM for measuring phytoplankton biomass was proven as effective as more traditional counting methods. However, calibration of the PhytoPAM throughout the experiment could accommodate shifting experimental conditions.

Experimenting with such an assemblage lacks the environmental realism of a natural aquatic food web, yet it does permit us to gain a deeper mechanistic understanding of cause-and-effect relationships. With the increasing likelihood of multiple and compound climatic pressures (e.g. IPCC, 2022), such experimental approaches can be key for elucidating relevant, underlying mechanisms of ecosystem processes. While experimental studies have demonstrated both antagonistic and (negative) synergistic climatic stressor interactions, phytoplankton communities may react differently when different climate scenarios are applied (Bergkemper et al., 2018; Richardson et al., 2019). Additionally, studies must incorporate geographic differences that will influence the form, frequency and severity in which stressors will manifest (e.g. Donat et al., 2016). Accounting for regional projections will guide what climatic scenarios are appropriate for assessing the probable pressures and reactions of a lake ecosystem.

Further research should focus on validating these mechanisms in more complex environmental settings, for example by using a mesocosm approach (e.g. Pace et al., 2019). Establishing this baseline understanding of coinciding climatic stressors on phytoplankton communities can support and inform the potential scenarios in real lake systems.

Supplemental information

S1. COMBO medium composition

COMBO medium (Kilham et al., 1998) was used as the basis of the microcosm environment with the addition of 3.5 L autoclaved COMBO in each of the cosms. This medium was similarly used for the replacement of all volume taken out of each microcosm during the sampling events. Further, COMBO medium was used in the laboratory-cultivation of the phytoplankton stocks that were used in this study. A table of compounds and volumes used in the COMBO medium are provided below. COMBO medium used directly in the experiment was created in 10 L batches.

Table S1: COMBO medium composition

COMBO medium composition (Kilham et al., 1998)

Major stock	mg/L
$CaCl_2$ $2H_2O$	36.76
$MgSO_4$ $7H_2O$	36.97
K_2HPO_4	8.71
$NaNO_3$	85.01
$NaHCO_3$	12.6
Na_2SiO_3 $9H_2O$	28.42
H_3BO_3	24
KCl	7.45

Algal trace elements	mg/L
Na_2EDTA $2H_2O$	4.36
$FeCl_3$ H_2O	1
$MnCl_2$ $4H_2O$	0.18
$CuSO_4$ $5H_2O$	0.001
$ZnSO_4$ $7H_2O$	0.022
$CoCl_2$ $6H_2O$	0.012
$NaMoO_4$ $2H_2O$	0.022
H_2SeO_3	0.0016
Na_3VO_4	0.0018

Animal trace elements	mg/L
LiCl	0.31
RbCl	0.07
$SrCl_2$ $6H_2O$	0.15

NaBr	0.016
KI	0.0033

Vitamins	mg/L
B_{12}	0.00055
Biotin	0.0005
Thiamin	0.1

S2. Precipitation simulation

We performed rainfall simulations with the Wageningen University + Research Soil Physics and Land Management Group rainfall simulator (Lassu et al., 2015) to attain a realistic scenario for soil runoff. The two simulations of an average Dutch precipitation event versus an extreme event were run in the simulator with matching set-ups. In both cases, nine sample containers containing soil from Omloop Lake, a eutrophic, man-made deep lake near de Bilt (51°47’34” N 004°57’6.8” E), were placed in a grid pattern within the simulation area. All soil containers were supersaturated preceding the rainfall simulation and situated at a 10% slope. Rainfall gauges were placed next to all of the soil containers for assessing evenness of precipitation distribution within the simulation area. An open-faced funnel collected the surface water and soil mobilized during the 26 minute simulations. The volume of collected runoff soil was calculated after drying for 24 h at 50 °C. Application of the surface area:lake area ratio of Omloop Lake to the microcosms resulted in the addition of a runoff solution of 600 mL demineralized water and 2.9 g soil to each microcosm with extreme precipitation scenarios.

S3. Psenner soil analysis

Soil utilized in the runoff simulation was analyzed for nutrient content, including phosphorus. Fractionation of phosphorus was assessed according to the adjusted Psenner soil analysis as outlined in (Cavalcante et al., 2018). Values are presented in the table below.

Table S3. Psenner soil phosphorus fractionation, as expressed in PO4-P mg/L

H_20 fraction		**BD* Fraction**		**NaOH fraction**		**HCl Fraction**		**Residual Fraction**	
SRP	TP	SRP	TP	SRP	TP	SRP	TP	SRP	TP
0.12	0.17	1.90	1.85	1.12	1.41	2.69	0.603	2.58	0.54

S4. Phytoplankton chlorophyll fluorescence

Our experiment utilized a PhytoPAM for measuring chlorophyll fluorescence of the phytoplankton species for all samples taken throughout the duration of the experiment (Figures S4A-C). This method was tested against the Coulter counter method to assess the values each method yielded. For each of the three experimental species, fluorescence was demonstrated to yield results similar to that of the Coulter counter method, supporting the validity of the fluorescence method for analyzing the microcosm experiment samples.

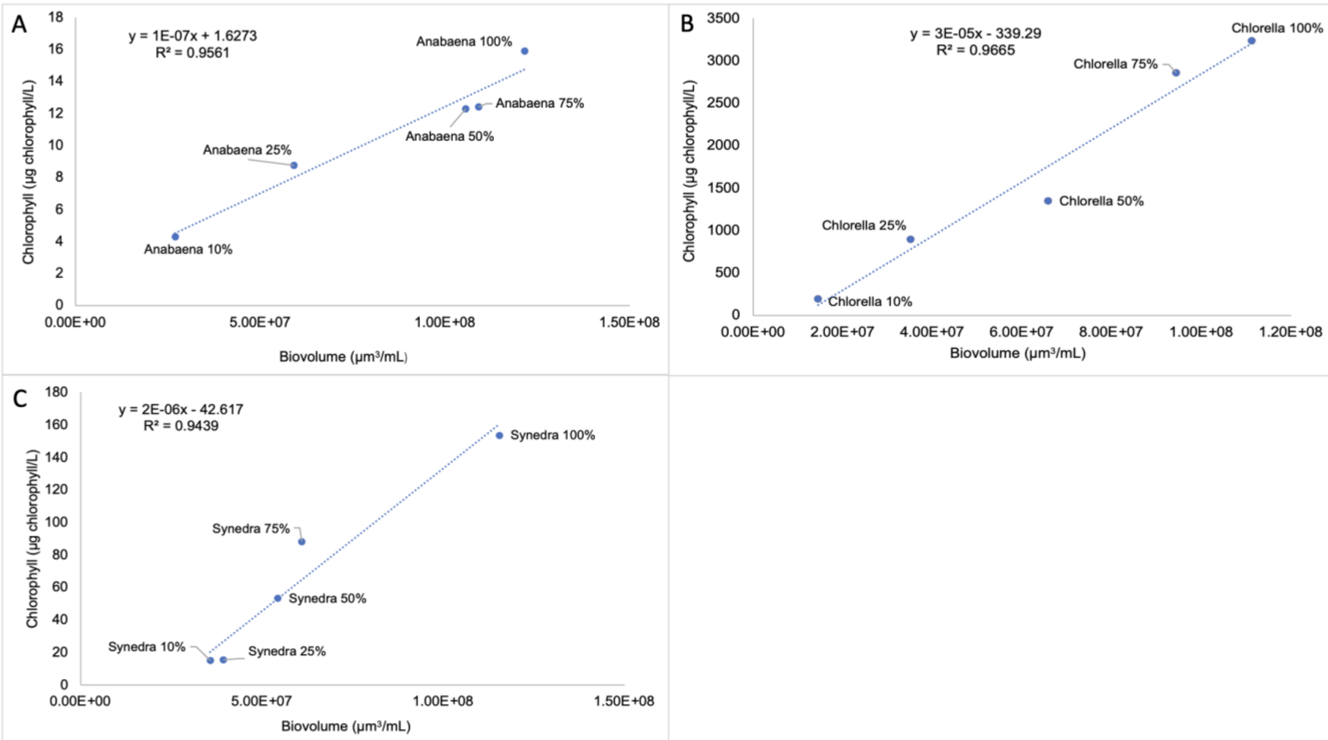


Figure S4: Comparison of fluorescence versus Coulter counter results with phytoplankton species *Anabaena flos-aquae* (**A**), *Chlorella vulgaris* (**B**) and *Synedra sp.* (**C**).

S5. Phytoplankton and dissolved nutrient dilution

To correct for dilution, we carried out two calculations:

Correction for sampling with replacement: For each sampling event and experimental unit, we corrected the concentration of Total Chlorophyll a, Dissolved Phosphorus and Dissolved Nitrogen using the sampling volume replacement (with equivalent volumes of COMBO medium).

$$\begin{aligned} &\mathit{Sampling\ diluted\ concentration} \\ &\qquad = (\mathit{concentration\ prior\ to\ sampling\ event} - \mathit{concentration\ of\ sample}) \\ &\qquad + \mathit{concentration\ of\ volume\ replacement} \end{aligned}$$

The dashed lines in Fig S5.1-S5.3 display these corrected concentrations averaged for the respective treatment.

Estimated correction for run-off event: For the microcosms that were exposed to the runoff events, we estimated the potential additional dilution due to the runoff event.

$$\mathit{Estimated\ runoff\ diluted\ concentration} = \frac{\mathit{mass\ present\ in\ volume}}{\mathit{volume\ after\ runoff\ event}}$$

As this was a one-time only event and based on values prior to the run-off event, the estimated correction for run-off event is visualized as a black dot in Fig S5.1-S5.3 as an average for the different temperature treatments.

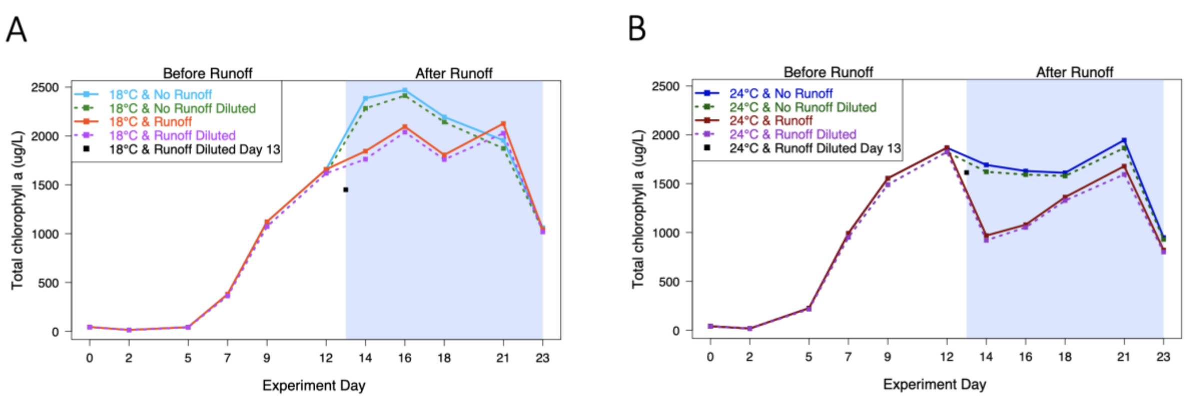


Figure S5.1 Sampled versus dilution corrected concentrations of Total Chlorophyll a by Treatment

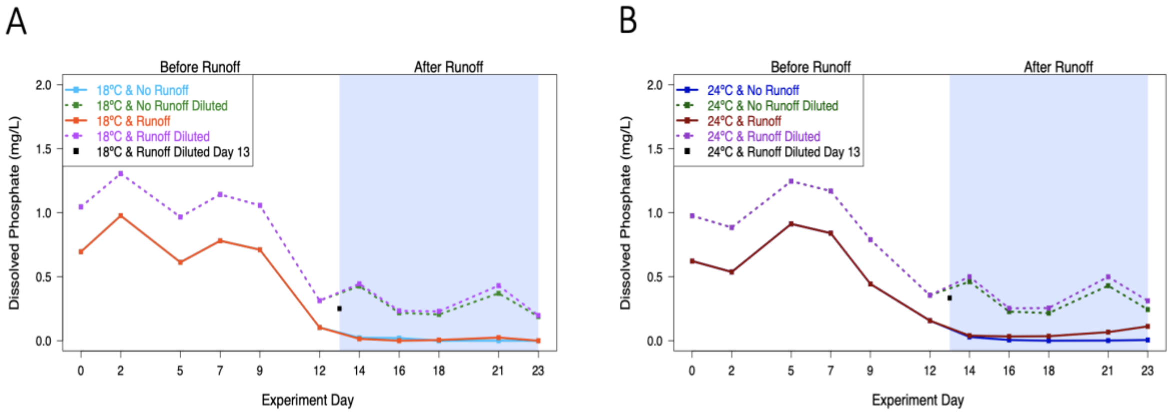


Figure S5.2 Sampled versus dilution corrected concentrations of Dissolved Phosphorus by Treatment

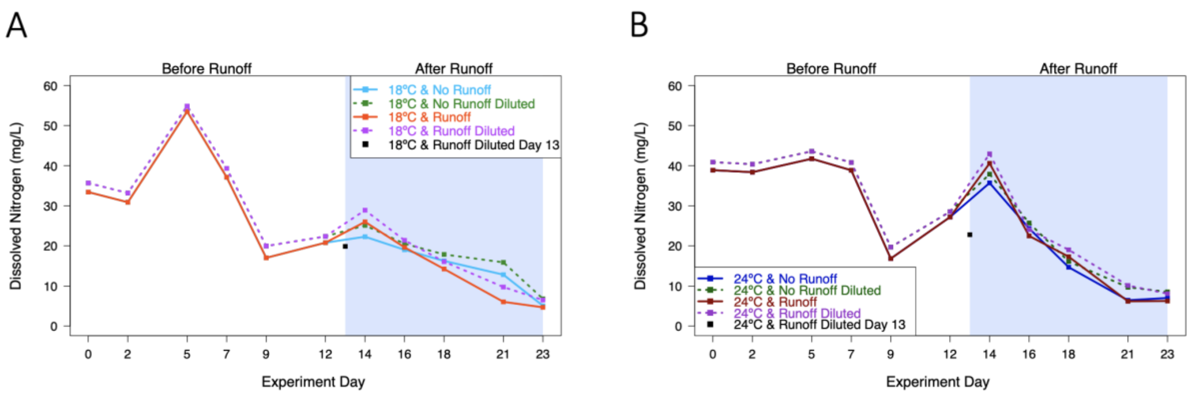


Figure S5.3 Sampled versus dilution corrected concentrations of Dissolved Nitrogen by Treatment

S6. Statistical Analysis

Additional statistical analyses were conducted to ascertain interactions and random effects for select experimental parameters. Tables include model results for intraclass correlation (ICC), residuals and AIC values. For the interaction term, this was calculated using the following model structure for all variables:

LME model: Response variable ~ Temp_levelExt×ExperimentDay×Precip_levelExP + (1|MicrocosmID)

The additional statistical analyses were applied for the following parameters: Total Chlorophyll a, *Anabaena flos-aquae*, *Chlorella vulgaris*, *Synedra sp.*, Particulate and Dissolved Phosphorus, Particulate and Dissolved Nitrogen, Phosphate, Dissolved Nitrogen, Particulate Phosphorus and Particulate Nitrogen.

Table S6.1 Total Chlorophyll a Statistical Analysis

Total Chlorophyll a	Full dataset (Days 0-23)					Before runoff (Days 0-12)					After runoff (Days 14-23)				
Random effects	AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*			
	sd	ICC				sd	ICC				sd	ICC			
MicrocosmID	212.5	0.00954				0	0				484.3	0.4203592			
Residual	634					6.054					567.3				
Fixed effects															
	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value
(Intercept)	-30.0811	123.8681	234	-0.242848	0.8083	-274.58895	72.9139	118	-3.765934	0.0003	4549.86	618.1084	92	7.360942	0
Temp_levelExt	254.6423	175.1759	22	1.453638	0.1602	48.25663	103.11583	22	0.467985	0.6444	-2093.123	874.1373	20	-2.394502	0.0266
ExperimentDay	105.2241	9.4557	234	11.128081	0	140.32472	10.26041	118	13.67633	0	-137.88	31.3266	92	-4.401363	0
Precip_levelExP	3049.7158	672.6515	234	4.533872	0						-1541.646	874.1373	20	-1.763619	0.0931
Temp_levelExt:ExperimentDay	-21.56	13.3724	234	-1.612278	0.1082	32.73248	14.51041	118	2.255793	0.0259	89.428	44.3025	92	2.018566	0.0464
Temp_levelExt:Precip_levelExP	-2377.1916	951.2729	234	-2.498959	0.0131						11.397	1236.2169	20	0.009219	0.9927
ExperimentDay:Precip_levelExP	-171.8189	36.7231	234	-4.67877	0						71.285	44.3025	92	1.609051	0.111
Temp_levelExt:ExperimentDay:Precip_levelExP	102.029	51.9343	234	1.964579	0.0506						-8.959	62.6533	92	-0.142988	0.8866
Shapiro-Wilk's test	*p-value*					p-value					p-value				
	0.05349					0.008526					0.5723				

Table S6.2 *Anabaena flos-aquae* Statistical Analysis

Anabaena flos-aquae	Full dataset (Days 0-23)					Before runoff (Days 0-12)					After runoff (Days 14-23)				
	AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*			
	3860.607	<0.005				834.934	0.04043				846.8053	0.1884			
Random effects:	~1|MicrocosmID					~1|MicrocosmID					~1|MicrocosmID				
	sd	ICC				sd	ICC				sd	ICC			
MicrocosmID	153.1275	0.09048831				0.00169347	0.06918487				6.355603	0.415455			
Residual	384.9289					4.216495					7.137777				
Fixed effects	~Temp_level * ExperimentDay * Precip_level					~Temp_level * ExperimentDay					~Temp_level * ExperimentDay * Precip_level				
	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value
(Intercept)	-175.2154	78.94	234	-2.219603	0.0274	-58.9148	40.65543	118	-1.449125	0.15	16.6124	7.9037	92	2.1018509	0.0383
Temp_levelExt	164.2159	111.638	22	1.470967	0.1555	-147.41424	57.49546	22	-2.563929	0.0177	25.918582	11.17752	20	2.3188132	0.0311
ExperimentDay	50.2708	5.7831	234	8.692723	0	24.22497	5.5248	118	4.384768	0	0.604056	0.399514	92	1.5119783	0.134
Precip_levelExP	-236.824	408.5266	234	-0.579703	0.5627						-8.931647	11.17752	20	-0.7990723	0.4336
Temp_levelExt:ExperimentDay	22.09	8.1785	234	2.700981	0.0074	84.39054	7.81325	118	10.800955	0	-1.046503	0.564998	92	-1.8522257	0.0672
Temp_levelExt:Precip_levelExP	761.58	577.7439	234	1.318196	0.1887						-6.753497	15.8074	20	-0.4272364	0.6738
ExperimentDay:Precip_levelExP	16.2267	22.3078	234	0.727399	0.4677						0.422773	0.564998	92	0.7482741	0.4562
Temp_levelExt:ExperimentDay:Precip_levelExP	-62.6381	31.548	234	-1.98549	0.0483						0.208772	0.799027	92	0.2612829	0.7945

Table S6.3 *Chlorella vulgaris* Statistical Analysis

Chlorella vulgaris	Full dataset (Days 0-23)					Before runoff (Days 0-12)					After runoff (Days 14-23)				
	AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*			
	3833.297	<0.005				2497.386	0.02026				1613.014	<0.005			
Random effects:	~1|MicrocosmID					~1|MicrocosmID					~1|MicrocosmID				
	sd	ICC				sd	ICC				sd	ICC			
MicrocosmID	50.81723	0.2211598				238.6657	0.03247524				200.5185	0.3574528			
Residual	377.7955					34725.86					217.1905				
Fixed effects	~Temp_level * ExperimentDay * Precip_level					~Temp_level * ExperimentDay					~Temp_level * ExperimentDay * Precip_level				
	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value
(Intercept)	227.2374	65.554	234	3.466417	0.0006	31.8755	148.68067	118	0.214389	0.8306	3775.975	241.4673	92	15.637625	0
Temp_levelExt	-104.04	92.7073	22	-1.122242	0.2739	506.6159	220.2344	22	2.300349	0.0313	-3673.06	341.4863	20	-10.756096	0
ExperimentDay	28.4858	5.4783	234	5.199749	0	99.2836	13.47787	118	7.366418	0	-168.721	12.1565	92	-13.879068	0
Precip_levelExP	2788.7858	400.4127	234	6.964778	0						-757.55	341.4863	20	-2.218391	0.0383
Temp_levelExt:ExperimentDay	-31.7306	7.7475	234	-4.095596	0.0001	-135.4724	20.92348	118	-6.474656	0	163.778	17.1919	92	9.526434	0
Temp_levelExt:Precip_levelExP	-2914.5787	566.2691	234	-5.146985	0						654.635	482.9346	20	1.355536	0.1904
ExperimentDay:Precip_levelExP	-159.3408	21.844	234	-7.294499	0						37.866	17.1919	92	2.202556	0.0301
Temp_levelExt:ExperimentDay:Precip_levelExP	162.5856	30.892	234	5.263026	0						-32.923	24.3131	92	-1.354114	0.179

Table S6.4 *Synedra sp.* Statistical Analysis

Synedra sp.

	Full dataset (Days 0-23)					Before runoff (Days 0-12)					After runoff (Days 14-23)				
	AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*			
	3586.325	0.05349				2453.839	0.1776				786.4414	0.8583			
Random effects:	~1|MicrocosmID					~1|MicrocosmID					~1|MicrocosmID				
	sd	ICC				sd	ICC				sd	ICC			
MicrocosmID	86.08502	0.06488919				129.7412	0.1208507				5.124016	0.4874036			
Residual	225.7871					14696.88					5.402134				
Fixed effects	~Temp_level * ExperimentDay * Precip_level					~Temp_level * ExperimentDay					~Temp_level * ExperimentDay * Precip_level				
	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value
(Intercept)	-79.6152	45.7008	234	-1.742095	0.0828	-272.4413	580.1598	118	-0.4695971	0.6395	30.446708	6.025092	92	5.053318	0
Temp_levelExt	193.0162	64.6307	22	2.986447	0.0068	390.5727	585.3791	22	0.6672133	0.5116	1.154004	8.520767	20	0.135434	0.8936
ExperimentDay	25.8708	3.3861	234	7.640401	0	36.7279	48.5784	118	0.756053	0.4511	-0.527216	0.302367	92	-1.743632	0.0846
Precip_levelExP	506.1389	239.6117	234	2.11233	0.0357						-9.592774	8.520767	20	-1.125811	0.2736
Temp_levelExt:ExperimentDay	-11.5717	4.7886	234	-2.416513	0.0164	-0.753	49.023	118	-0.015361	0.9878	-0.360368	0.427611	92	-0.842748	0.4016
Temp_levelExt:Precip_levelExP	-229.0804	338.8621	234	-0.676028	0.4997						-1.857025	12.050185	20	-0.154108	0.8791
ExperimentDay:Precip_levelExP	-28.108	13.0834	234	-2.148366	0.0327						0.32618	0.427611	92	0.762795	0.4475
Temp_levelExt:ExperimentDay:Precip_levelExP	1.7337	18.5028	234	0.093701	0.9254						0.155998	0.604733	92	0.257962	0.797

Table S6.5 Particulate and Dissolved Phosphorus Statistical Analysis

Particulate and dissolved phosphorus

	Full dataset (Days 0-23)					Before runoff (Days 0-12)					After runoff (Days 14-23)				
	AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*			
	373.8411	0.02177				192.2546	0.1952				41.10798	0.5426			
Random effects:	~1|MicrocosmID					~1|MicrocosmID					~1|MicrocosmID				
	sd	ICC				sd	ICC				sd	ICC			
MicrocosmID	0	0.00387089				0	0				0.08816844	0.1415236			
Residual	0.4426976					0.4247395					0.213653				
Fixed effects	~Temp_level * ExperimentDay * Precip_level					~Temp_level * ExperimentDay					~Temp_level * ExperimentDay * Precip_level				
	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value
(Intercept)	0.9087861	0.0747751	234	12.153598	0	-0.3312224	0.08764478	118	-3.779145	0.0002	1.4986938	0.2263479	92	6.621195	0
Temp_levelExt	0.0513721	0.1057479	22	0.485798	0.6319	-0.1490144	0.12394843	22	-1.202229	0.2421	-0.3182126	0.3201043	20	-0.99409	0.3321
ExperimentDay	0.0037059	0.0063572	234	0.582955	0.5605	0.0228592	0.01233333	118	1.853448	0.0663	-0.0289124	0.0119585	92	-2.417725	0.0176
Precip_levelExP	-0.1201427	0.4690327	234	-0.25615	0.7981						-0.5353417	0.3201043	20	-1.672398	0.11
Temp_levelExt:ExperimentDay	0.0111799	0.0089904	234	1.243537	0.2149	0.0621181	0.01744196	118	3.561414	0.0005	0.0187218	0.0169119	92	1.107017	0.2712
Temp_levelExt:Precip_levelExP	-0.365704	0.6633125	234	-0.55133	0.5819						0.0623598	0.4526959	20	0.137752	0.8918
ExperimentDay:Precip_levelExP	-0.0014406	0.025581	234	-0.056317	0.9551						0.0245685	0.0169119	92	1.452734	0.1497
Temp_levelExt:ExperimentDay:Precip_levelExP	0.0057149	0.036177	234	0.157969	0.8746						-0.0048601	0.023917	92	-0.203206	0.8394

Table S6.6 Particulate and Dissolved Nitrogen Statistical Analysis

Particulate and dissolved nitrogen

	Full dataset (Days 0-23)					Before runoff (Days 0-12)					After runoff (Days 14-23)				
	AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*			
	2147.648	0				119.5031	0.06885				386.7699	0.8125			
Random effects:	~1|MicrocosmID					~1|MicrocosmID					~1|MicrocosmID				
	sd	ICC				sd	ICC				sd	ICC			
MicrocosmID	2.912631	0.07681969				0	0.02247444				0.4354557	0.1059088			
Residual	13.919					0.3275528					0.994744				
Fixed effects	~Temp_level * ExperimentDay * Precip_level					~Temp_level * ExperimentDay					~Temp_level * ExperimentDay * Precip_level				
	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value
(Intercept)	39.663	2.502608	234	15.848666	0	3.592706	0.06759034	118	53.15413	0	8.517615	1.0555182	92	8.069605	0
Temp_levelExt	3.81228	3.539222	22	1.077151	0.2931	0.05137	0.09558717	22	0.53742	0.5964	2.455306	1.4927282	20	1.644844	0.1156
ExperimentDay	-0.32272	0.203974	234	-1.582162	0.115	-0.007558	0.00951128	118	-0.7946	0.4284	-0.148665	0.0556775	92	-2.670101	0.009
Precip_levelExP	20.99405	14.758085	234	1.422546	0.1562						-0.050877	1.4927282	20	-0.034083	0.9731
Temp_levelExt:ExperimentDay	0.38756	0.288463	234	1.343549	0.1804	0.02271	0.01345098	118	1.68836	0.094	-0.088261	0.0787399	92	-1.120925	0.2652
Temp_levelExt:Precip_levelExP	30.33402	20.871084	234	1.4534	0.1475						-0.036503	2.1110364	20	-0.017291	0.9864
ExperimentDay:Precip_levelExP	-1.18181	0.80533	234	-1.467492	0.1436						-0.006042	0.0787399	92	-0.076728	0.939
Temp_levelExt:ExperimentDay:Precip_levelExP	-1.99849	1.138908	234	-1.754741	0.0806						-0.023271	0.111355	92	-0.208983	0.8349

Table S6.7 Phosphate Statistical Analysis

Dissolved phosphate (PO4)

	Full dataset (Days 0-23)					Before runoff (Days 0-12)					After runoff (Days 14-23)				
	AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*			
	206.6128	0				185.816	0				-210.5727	0			
Random effects:	~1|MicrocosmID					~1|MicrocosmID					~1|MicrocosmID				
	sd	ICC				sd	ICC				sd	ICC			
MicrocosmID	0	0				0	0				0.03777688	0			
Residual	0.3193441					0.415084					0.06746282				
Fixed effects	~Temp_level * ExperimentDay * Precip_level					~Temp_level * ExperimentDay					~Temp_level * ExperimentDay * Precip_level				
	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value
(Intercept)	0.9009082	0.0539397	234	16.702134	0	0.913052	0.08565236	118	10.659975	0	0.0602005	0.07222762	92	0.8334831	0.4067
Temp_levelExt	-0.1090648	0.0762823	22	-1.429754	0.1668	-0.1447411	0.12113072	22	-1.194917	0.2448	-0.0125013	0.10214527	20	-0.122387	0.9038
ExperimentDay	-0.0463648	0.0045858	234	-10.110543	0	-0.0456518	0.01205296	118	-3.787599	0.0002	-0.0028008	0.00377601	92	-0.7417227	0.4601
Precip_levelExP	-0.8909821	0.3383412	234	-2.633383	0.009						-0.0502744	0.10214527	20	-0.4921856	0.6279
Temp_levelExt:ExperimentDay	0.0068957	0.0064853	234	1.063282	0.2887	0.0142985	0.01704546	118	0.838844	0.4033	0.00066855	0.00534008	92	0.125194	0.9006
Temp_levelExt:Precip_levelExP	0.0102867	0.4784868	234	0.021498	0.9829						-0.0862769	0.14445523	20	-0.5972573	0.557
ExperimentDay:Precip_levelExP	0.0463091	0.0184531	234	2.509553	0						0.00274499	0.00534008	92	0.5140345	0.6085
Temp_levelExt:ExperimentDay:Precip_levelExP	0.0011049	0.0260967	234	0.04234	0.9663						0.00733208	0.00755202	92	0.9708768	0.3342

Table S6.8 Dissolved Nitrogen Statistical Analysis

						Dissolved nitrogen (=NO2+NO3+NH4)									
	Full dataset (Days 0-23)					Before runoff (Days 0-12)					After runoff (Days 14-23)				
	AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*			
	2067.73	0				184.772	0.2817				-367.5403	0.8958			
Random effects:	~1|MicrocosmID					~1|MicrocosmID					~1|MicrocosmID				
	sd	ICC				sd	ICC				sd	ICC			
MicrocosmID	0.00068934	0				0	0				0.0051482	0			
Residual	12.10366					0.4135393					0.0361033				
Fixed effects	~Temp_level * ExperimentDay * Precip_level					~Temp_level * ExperimentDay					~Temp_level * ExperimentDay * Precip_level				
	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value
(Intercept)	40.24479	2.044402	234	19.685357	0	3.63261	0.08533361	118	42.56951	0	-0.1804809	0.03782024	92	-4.772072	0
Temp_levelExt	2.45102	2.891221	22	0.847745	0.4057	0.069264	0.12067994	22	0.57395	0.5718	-0.0282484	0.05348589	20	-0.528147	0.6032
ExperimentDay	-1.37818	0.173809	234	-7.929271	0	-0.048998	0.0120081	118	-4.08039	0.0001	0.01493471	0.00202076	92	7.390626	0
Precip_levelExP	18.80769	12.82368	234	1.466637	0.1438						-0.1035652	0.05348589	20	-1.936308	0.0671
Temp_levelExt:ExperimentDay	-0.06593	0.245803	234	-0.268226	0.7888	0.003019	0.01698202	118	0.17776	0.8592	0.00138008	0.00285779	92	0.482918	0.6303
Temp_levelExt:Precip_levelExP	24.35341	18.135423	234	1.342864	0.1806						0.07344178	0.07564047	20	0.970932	0.3432
ExperimentDay:Precip_levelExP	-1.06403	0.699403	234	-1.521338	0.1295						0.0069269	0.00285779	92	2.423866	0.0173
Temp_levelExt:ExperimentDay:Precip_levelExP	-1.14938	0.989106	234	-1.16204	0.2464						-0.0050849	0.00404153	92	-1.258155	0.2115

Table S6.9 Particulate Phosphorus Statistical Analysis

						Particulate phosphorus									
	Full dataset (Days 0-23)					Before runoff (Days 0-12)					After runoff (Days 14-23)				
	AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*			
	273.1331	0				-123.2562	0.1012				44.16831	0.6485			
Random effects:	~1|MicrocosmID					~1|MicrocosmID					~1|MicrocosmID				
	sd	ICC				sd	ICC				sd	ICC			
MicrocosmID	0	0				0	0				0.09103586	0.1624173			
Residual	0.3636499					0.1376414					0.2162326				
Fixed effects	~Temp_level * ExperimentDay * Precip_level					~Temp_level * ExperimentDay					~Temp_level * ExperimentDay * Precip_level				
	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value
(Intercept)	0.0078779	0.0614233	234	0.128256	0.8981	0.14894822	0.02840223	118	5.244244	0	1.468266	0.2291991	92	6.406073	0
Temp_levelExt	0.1604369	0.0868657	22	1.846955	0.0782	0.00988053	0.04016682	22	0.245987	0.808	-0.3107192	0.3241364	20	-0.958606	0.3492
ExperimentDay	0.0500708	0.005222	234	9.588385	0	0.05341545	0.00399675	118	13.364729	0	-0.0274956	0.0121029	92	-2.271816	0.0254
Precip_levelExP	0.7708394	0.3852827	234	2.000711	0.0466						-0.5127728	0.3241364	20	-1.581966	0.1293
Temp_levelExt:ExperimentDay	0.0042842	0.0073851	234	0.580112	0.5624	0.0293581	0.00565226	118	5.19405	0	0.0182661	0.0171161	92	1.067189	0.2887
Temp_levelExt:Precip_levelExP	-0.3759907	0.544872	234	-0.690053	0.4908						0.1136511	0.4583981	20	0.247931	0.8067
ExperimentDay:Precip_levelExP	-0.0477497	0.0210133	234	-2.272356	0.024						0.0233172	0.0171161	92	1.362294	0.1764
Temp_levelExt:ExperimentDay:Precip_levelExP	0.0046099	0.0297173	234	0.155126	0.8769						-0.009227	0.0242058	92	-0.38119	0.7039

Table S6.10 Particulate Nitrogen Statistical Analysis

						Particulate nitrogen									
	Full dataset (Days 0-23)					Before runoff (Days 0-12)					After runoff (Days 14-23)				
	AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*				AIC	normality test of residual *(Shapiro-Wilk)*			
	1893.736	0				148.6653	0.6171				429.1078	0.6634			
Random effects:	~1|MicrocosmID					~1|MicrocosmID					~1|MicrocosmID				
	sd	ICC				sd	ICC				sd	ICC			
MicrocosmID	2.811273	0.04572032				0	0				0.7069473	0.2983659			
Residual	8.329203					0.3635074					1.162084				
Fixed effects	~Temp_level * ExperimentDay * Precip_level					~Temp_level * ExperimentDay					~Temp_level * ExperimentDay * Precip_level				
	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value	Value	Std. Error	DF	t-value	p-value
(Intercept)	-0.575695	1.630224	234	-0.353139	0.7243	0.1275688	0.07500957	118	1.7007	0.0916	4.221376	1.2492625	92	3.379095	0.0011
Temp_levelExt	1.354335	2.305485	22	0.58744	0.5629	0.1077778	0.10607955	22	1.016009	0.3207	0.733898	1.7667239	20	0.4154	0.6823
ExperimentDay	1.053997	0.124266	234	8.4818	0	0.19172	0.01055531	118	18.163373	0	0.002835	0.0650438	92	0.04359	0.9653
Precip_levelExP	2.206896	8.837392	234	0.249723	0.803						-1.48497	1.7667239	20	-0.840522	0.4106
Temp_levelExt:ExperimentDay	0.455155	0.175738	234	2.589962	0.0102	0.0683453	0.01492746	118	4.578495	0	0.003805	0.0919859	92	0.041369	0.9671
Temp_levelExt:Precip_levelExP	5.957278	12.49796	234	0.47666	0.634						-0.060727	2.4985249	20	-0.024305	0.9808
ExperimentDay:Precip_levelExP	-0.116325	0.482477	234	-0.2411	0.8097						0.072541	0.0919859	92	0.78861	0.4324
Temp_levelExt:ExperimentDay:Precip_levelExP	-0.850768	0.682326	234	-1.246865	0.2137						-0.036889	0.1300877	92	-0.283568	0.7774

S7. Turbidity

Turbidity measurements were taken once per week throughout the duration of the experiment using a WTW Turb430IR Meter (WTW, Weilheim, Germany). Immediately upon addition of the runoff solution, the treated microcosms became murky, which contributed to a significant effect of precipitation treatment on turbidity in the period after the runoff event ($F_{1,20} = 5.45$, $p = 0.03$).

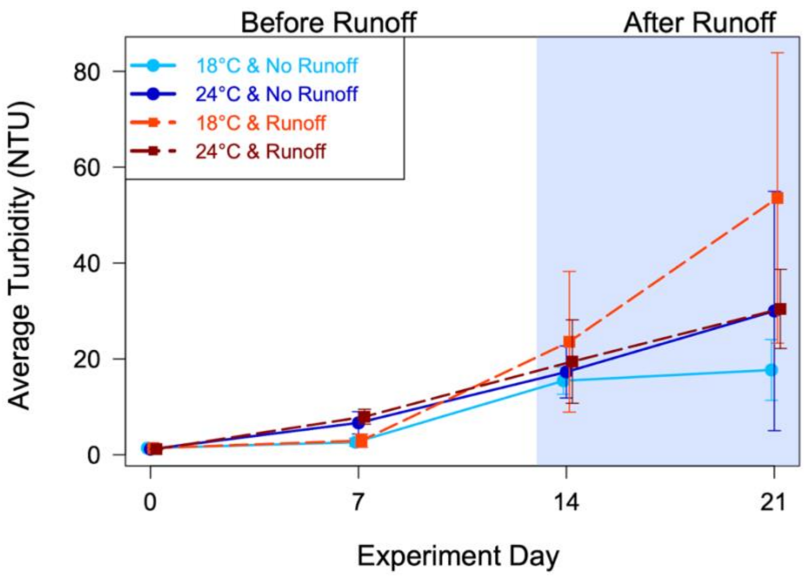
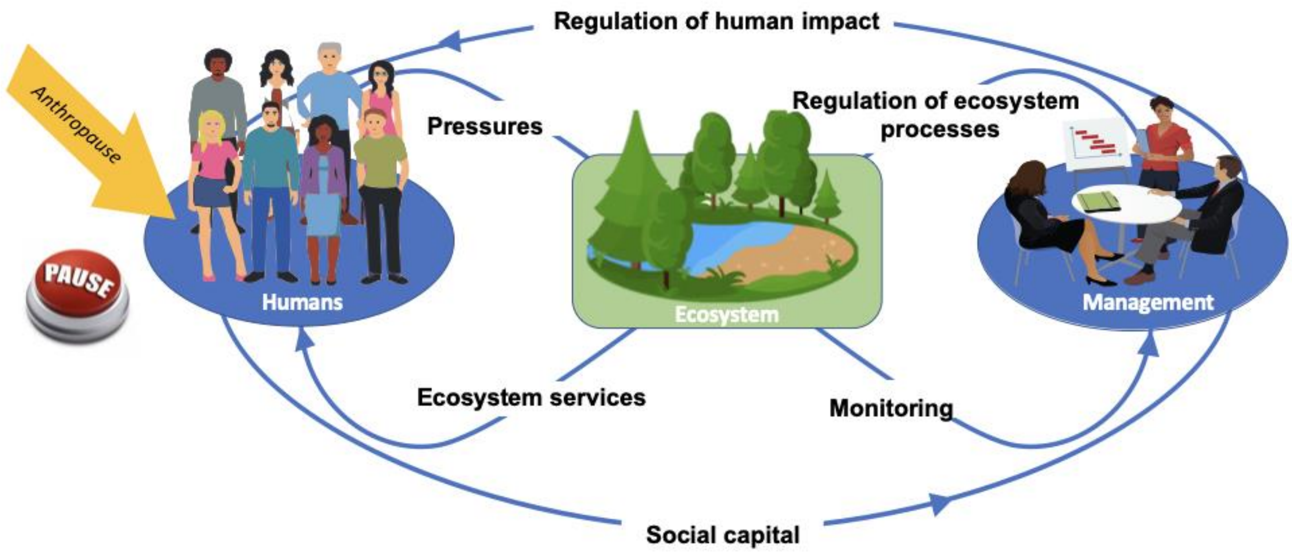


Figure S7: Average turbidity (NTU) of microcosms by treatment

Chapter Two -
Making Waves: Lessons learned from the COVID-19 anthropause for water quality management

Armstrong, M., Aksu Bahçeci, H., van Donk, E., Dubey, A., Frenken, T., Gebreyohanes Belay, B.M., Gsell, A.S., Heuts, T.S., Kramer, L., Lürling, M., Ouboter, M., Seelen, L.M.S., Teurlincx, S., Vasantha Raman, N., Zhan, Q., and de Senerpont Domis, L.N. (2022) Making waves: Lessons learned from the COVID-19 anthropause in the Netherlands on urban aquatic ecosystem services provisioning and management. Published in Water Research,
DOI: 10.1016/j.watres.2022.118934

Graphical Abstract



1. Welcome to the anthropause

The anomalous past two years of the coronavirus (COVID-19) pandemic have been a test of human response to global crisis management as typical human activities were significantly altered (Searle et al., 2021). This phenomenon, coined an "anthropause" (Rutz et al., 2020), can be viewed as an intentional and abrupt cessation of human behavior patterns in response to disruption from a pandemic (COVID-19), pollution disaster (Chernobyl), environmental catastrophe (Hurricane Katrina) or military intervention (Korean demilitarized zone; Searle et al., 2021). Few times in recorded human history has such a pause occurred at this all-encompassing global and sectoral scale while also being well-documented.

Efforts to contain COVID-19 have resulted in varying degrees of national interventions to limit human contact that ranged from social-distancing measures to selective travel restrictions to full lockdowns (Primc & Slabe-Erker, 2020). In Europe, most countries imposed various mobility restrictions from spring 2020-winter 2021, with the severity of the restrictions following the wax and wane of the recorded infections. In contrast to other notorious but localized anthropauses (Fukushima), the COVID-19 anthropause has resulted in drastic, widespread reduction of some human activities (traveling; March et al., 2021) and increases in others (recreation in urban nature spaces; Venter et al., 2020).

Our water systems have demonstrated a ripple effect of the COVID-19 anthropause on the biosphere. Some of the shifts and reductions in human activities have been attributed to positive system changes, such as moratoriums of industrial heavy metal pollution or reduced commercial fishing pressures (Mandal et al., 2020). However, not all anthropause trends provided a respite for aquatic systems. Human activities have also negatively affected water systems such as with beach overcrowding instigating littering (Miller-Rushing et al., 2021; Zielinski & Botero, 2020) and publicly-applied disinfectants entering surface waters (Chu et al., 2021).

All water systems are uniquely defined by their location, hydromorphology, human use and management approach (Wetzel, 2001). Ergo, the types of systems being studied (e.g. inland or coastal, lentic or lotic, temperate or tropical, etc.) will influence which of the COVID-19 effects have been observed and what water management take-away message this anthropause has had. Water systems in heavily urbanized areas, for instance, are inundated with continuous pressures stemming from constant exposure to human activities, infrastructure and now pandemic management. Attaining an overview of COVID-19 impacts on urban waters is therefore relevant for human management of, and engagement with, these systems while also presenting outlooks on a future in a more urbanized world.

While undesirable, COVID-19 provided a unique opportunity for studying effects of changing human pressures and uses within human-ecosystem interactions. Under present pandemic conditions, these interactions are susceptible to change due to altered opportunities, capability and motivation for humans to engage with nature (Soga et al., 2021). Restrictions from COVID-19 mandates could, for instance, either alleviate some pressures to these systems by reducing human interactions or could contribute to the pressures with increased human demand due to continued access to the ecosystem. Knowledge gathered during this time can be monumental for informing and improving management and policy regarding adaptation to a more urbanized world with higher likelihoods of pandemics (de Senerpont Domis & Teurlincx, 2020), time delays of pandemic repercussions (Soga et al., 2021) and to adoption of more sustainable practices for ecosystems (Folke et al., 2021). The implications of informed management on human-ecosystem interactions can support mutually beneficial feedback for both society and nature (e.g. Pereira et al., 2020), as has been suggested in the context of social-ecological models (Mooij et al., 2019). In reviewing literature from the COVID-19 anthropause, we saw a lag in the number of papers aimed at discerning the effects of the pandemic on surface waters in highly urbanized areas. Below, we address this gap by reflecting on the implications that the pandemic anthropause has had on the human-ecosystem-management interactions by defining this relationship and presenting case studies of recreational service demands for water bodies in the Netherlands. Finally, from the case study observations and with evidence from recent literature, we derive management lessons regarding best practices for future implementation.

2. Conceptual framing of human-ecosystem-management interactions

The sheer magnitude of human influence on the biosphere in this epoch is evident in its delineation as the "Anthropocene" (Trischler, 2016) and the COVID-19 lockdown period as an "anthropause." August 2021 saw the IPCC unequivocally attribute climate change to human actions and register this pressure as "code red" (IPCC, 2021). Cumulative human activities across the planet have also manifested as habitat degradation by way of land use change (de Senerpont Domis & Teurlincx, 2020), biodiversity loss and overall incapability of ecosystems to handle variability in pressures (Folke et al., 2021).

These human-ecosystem interactions are a two-way feedback wherein the biosphere also affects human wellbeing and behaviors (Folke et al., 2021). Societies are dependent upon stability in ecosystem functioning (Comberti et al., 2015) and provisioning of services (e.g. benefits such as food, recreation, nutrient cycling; de Senerpont Domis & Teurlincx, 2020) as outlined in frameworks on the interdependence of human, animal and environmental health (One Health triad, Ecohealth transdisciplinary approach; Rabinowitz et al., 2018, Zinsstag, 2012). For example, environmentally healthy urban aquatic systems pose less risk for cyanotoxin poisoning of wildlife, pets and humans (e.g. Merel et al., 2013). Perpetuating the fallacy of perceiving humans as separate from the biosphere will lead to societal destabilization through the collapse of ecosystem functions (Rockström et al., 2009), as is already illustrated with the negative feedback of deteriorating water system functions on present day societies (Folke et al., 2021).

Management of aquatic ecosystems requires accounting for the interlinked connections between human-built and natural systems. Separately, these two types of systems span numerous sectors and are based on complex connections amongst various drivers, demands and feedbacks (DPSIR framework; Tscherning et al., 2012). However, considering the implications of one system in isolation from the other is a disservice to both humans and the biosphere as there can be connections and repercussions between the interlinked systems that are unaccounted for. Understanding and working with both types of systems, particularly with elaborating on the feedback from human-nature interactions (ecosystem services and services-to-ecosystems connections; Comberti et al., 2015), can facilitate beneficial outcomes to ecosystem functioning and human uses. Frameworks such as the IPBES Conceptual Framework (Díaz et al., 2015) integrate knowledge from multiple sources by making explicit linkages between the elements of human well-being, biodiversity and ecosystems, ecosystems goods and services, natural and anthropogenic drivers, and anthropogenic assets. Further, the framework draws the connection of this knowledge to governance and decision-making.

3. Changes to ecosystem service demand

Human settlements have a long history of placement in proximity to water systems, including today with over 50% of the global population living within 3km of freshwater bodies (Kummu et al., 2011) and with many urban centers still situated in relation to rivers (Di Baldassarre et al., 2013), lakes (Trudeau & Richardson, 2016) and other water bodies. The biosphere's water systems are capable of providing abundant ecosystem services, though limitations can arise depending upon the degree of ecosystem functioning, the rate of service exploitation and if there is demand for competing finite water services or resources. During the COVID-19 anthropause there have been abrupt shifts in typical service demands in response to local pandemic measures, such as with use of blue spaces for recreation. We will illustrate examples of changes in ecosystem demand under the COVID-19 anthropause with four case studies from Dutch water systems. In the Netherlands, strict pandemic restrictions starting 15 March 2020 resulted in episodic closing of schools and non-essential businesses, restricted international traveling, limited house visits and social-distancing ("COVID-19 Pandemic in the Netherlands," 2021). These restrictions bore consequences for outdoor activities due to changing demand for aquatic cultural services of recreational boating and swimming (CICES 6.1.1.1), recreational fishing (CICES 1.1.6.1), and shoreline walking (CICES 3.1.1.2; classification codes from CICES version 5.1; see Seelen et al., 2022).

3.1. Decreased human activities: recreational boating

The reduction of recreational boating in Amsterdam canals during the pandemic had an impact on the underwater ecosystem. A large portion of this reduced pressure has been attributed to the suspension of international tourism (*International Tourism and Covid-19*). Boating traffic data was obtained from the tracking of receiver-outfitted boats through the municipality of Amsterdam's "The Digital Canal" programme (*De Digitale Gracht*) to discern general trends of boat movement. Water transparency data was collected biweekly through Secchi depth readings by the Amstel, Gooi and Vecht water authority's monitoring programme. Figure 1 shows the coinciding trends in water quality and boat traffic. With less boat activity in the canals since the first lockdown in March 2020, there was an observed decrease in resuspension of solid matter resulting in an increase in water clarity relative to previous years (Figure 1A-C). The increased light penetration permitted the establishment of submerged macrophytes (Figure 1D; *Amsterdamse Grachten Helderder Dan Ooit Dankzij Coronamaatregelen*, 2020), demonstrating that the diminished demand for one service (boating) reduced pressure exerted upon the ecosystem and created the conditions for improving another service (habitat).

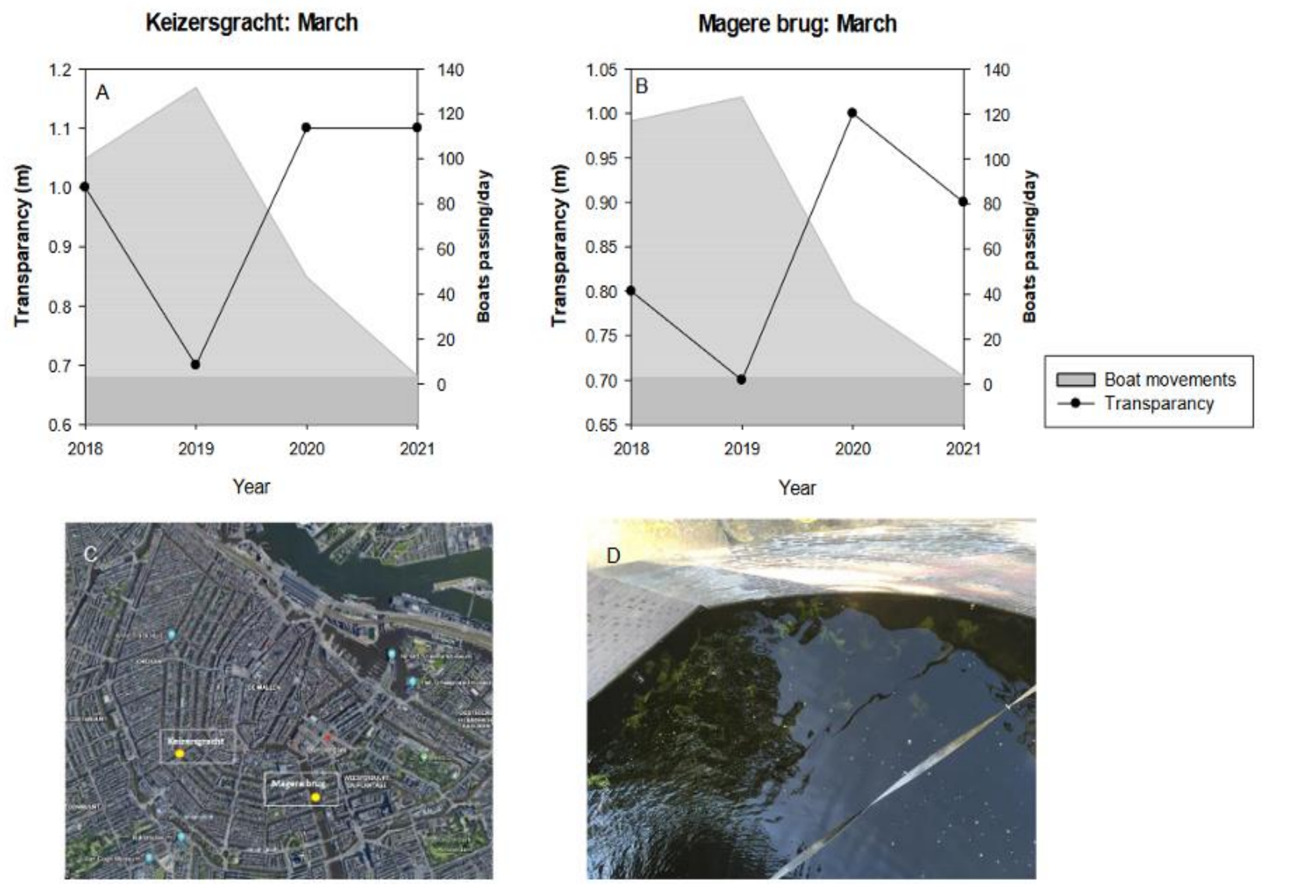


Figure 1: Shifts in Amsterdam canal water transparency versus boating traffic. 2018-2021 average March water transparency versus boating activity at Magere brug (**A**) and Keizersgracht (**B**). Map of the locations **(C)**. *Nuphar lutea* growth in Keizersgracht (7-5-2020) **(D)**. Water transparency data were averaged from biweekly Secchi disc readings collected by the Regional Public Water Authority Amstel, Gooi and Vecht as part of their water quality monitoring programme. Boating traffic data was collected from receiver-outfitted boats passing through remotely monitored sections of the canals, as managed by the municipality of Amsterdam's project "The Digital Canal."

3.2. Increased human activities: fishing, bathing and national park visits

During the pandemic, some human activities intensified as people were seeking solace in the outdoors (Venter et al., 2020). In the Netherlands, outdoor physical activities were not restricted and therefore public outdoor spaces were possibly utilized more. In contrast to boating, other recreational activities (fishing, bathing and national park visits) saw a perceived increase in demand during the anthropause as compared to previous years. Alterations of service demand for fishing, bathing and national park visits were not directly or uniformly measured as boating had been. We therefore validated this perceived change in services demand with different sources of proxy data to derive shifts in human interests. Case study data is available at https://doi.org/10.5281/zenodo.6551591.

Annual numbers of fishing licenses sold, as reported by Sportvisserij Nederland (Royal Dutch Angling Association), was utilized as proxy data for the number of people interested in or utilizing fishing services. We compared reported regional numbers from 2016-2020 to trace shifts in trends (visualized with ggplot2). Figure 2A illustrates an increase in licenses sold during 2020 as compared to previous years. As there were no alterations to fishing legislation, license accessibility and license prices during the COVID-19 pandemic, we infer that the increase in licenses sold is due to an increased demand during the anthropause. While humans can benefit mentally and physically from such recreational activities (Venter et al., 2020), environmental repercussions can arise if the activities are not managed. For instance, having an increased number of anglers using a limited number of fishing locations can negatively affect fish through the more frequent exertion of stress, even with catch-and-release practices (Brownscombe et al., 2017). Additionally, having a finite number of sanctioned fishing locations could instigate angling in undesignated, unmanaged water systems. Further, unsanctioned practices could occur with self-stocking of angling or bait fish in the water system, effectively altering the local food web dynamic (Matern et al., 2018).

Bathing water areas similarly garnered more public interest during the anthropause, as derived from proxy data comparing public interest through the measure of Google search trends before and during the pandemic (search term “zwemmen buiten” (English translation: “swimming outside”) from 2016 to 2020 searched on 4 October 2021; Figure 2B). We visualized the trends in searches for bathing waters and compared the pre-pandemic data to the pandemic period using a LOESS smoothing function (Jacoby, 2000) and Wilcoxon signed rank test (*wilcox.test: Wilcoxon Rank Sum and Signed Rank Tests*). Assuming that increased search behavior translates in increased human traffic (e.g. Clark et al., 2019) at the swimming sites, the increased demand raises concern over the risk of spreading COVID-19 with numerous individuals from different households being in close proximity at these sites (*Publieksvoorlichting*, 2021). Other health risks are also concerning as the demand for bathing opportunities can lead to people swimming in non-designated sites. As these unsanctioned locations are not subject to monitoring under the European Union’s Bathing Directive, swimmers can be exposed to pathogens and contract illnesses. From an environmental perspective, there is the omnipresent concern that increases in crowds heighten the likelihood of pollutants such as microbial exposure and increased turbidity (e.g. Graczyk et al., 2010). From the pandemic, additional concerns arise with macro- or microplastics from littered personal protective gear (Ammendolia et al., 2021) being introduced into the system and affecting the biota (Parashar & Hait, 2021).

Alterations in accessibility of urban water services during the pandemic, such as through the closure or limited capacity of recreation areas, could lead to increased use of blue-green spaces outside of city limits. Google search trends for national park locations was used as a proxy dataset for human demand in shoreline walking (trend data for the park names from 2016 to 2020 searched on 3 June 2021; Figure 2C). 2020 pandemic data was visualized and compared against pre-pandemic data using the LOESS smoothing function (Jacoby, 2000) and Wilcoxon signed rank test (*wilcox.test: Wilcoxon Rank Sum and Signed Rank Tests*). Interest in Dutch national parks containing wetlands or open water systems was perceived to increase during the anthropause as compared to previous years. Given the connection between blue-green spaces and mental health (Pouso et al., 2021), it can be hypothesized that prolonged immobility in urban centers (the anthropause) can bolster an interest in spending time in blue-green spaces, including systems in non-urban areas. With the observed shift in water systems use, there are concerns about pressures that could be introduced with the increased demand. Similar to bathing waters, increased water system use can lead to increased littering (Parashar & Hait, 2021). Further concerns include the additional anthropogenic noise pollution (Templeton et al., 2021) from more visitors disturbing inhabitants (fish, birds, mammals) and the increased foot traffic causing physical wear of shorelines and pathways (Salesa & Cerdà, 2020).

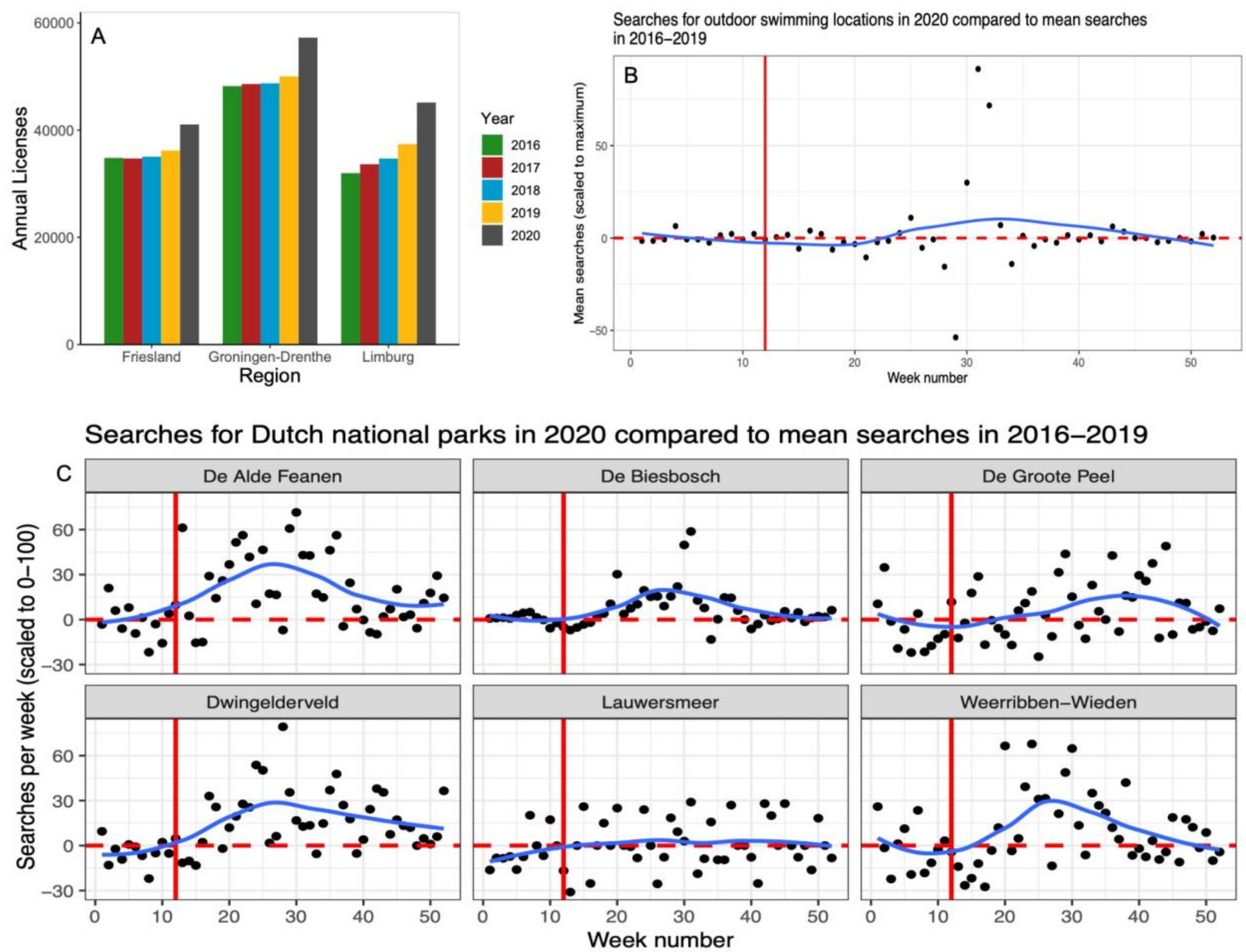


Figure 2: Changes in Dutch aquatic recreation before and during the COVID-19 anthropause. Shifts are shown with **A.** annual fishing licenses for ages 6+ from 2016 to 2020 by Netherlands regions (Sportvisserij Nederland; R package *ggplot2*, Wickham et al., 2021), **B.** recreational swimming and **C.** national parks containing water systems. Weekly Google trend search frequencies during 2020 (black dots) were scaled and compared to the average weekly search frequencies for 2016-2019 (dashed red horizontal line) to illustrate deviations from previous years. A LOESS smoothing function (Jacoby, 2000) for the 2020 data is applied (blue line). The start of the 2020 anthropause is delineated (red vertical line). In the Netherlands, the pandemic started with the first recorded infection in February 2020 and the anthropause with the enactment of stringent mobility restrictions and social distancing in March 2020 ("COVID-19 Pandemic in the Netherlands," 2021).

4. Lessons learned from the anthropause for water quality management

The COVID-19 anthropause permitted an unplanned experiment with shifted human pressures on water systems, the first of its kind in the Anthropocene (Chowdhury et al., 2021). In some systems, the anthropause has shown us visions of desirable futures (Pereira et al., 2020). As society hits "play" from this anthropause, distilling the management lessons learned from the pandemic-induced shift in human-ecosystem interactions in order to maintain the positive social and ecological COVID-19 outcomes in water systems will be important, both for immediate and future management applications. Anthropause-derived insights should therefore be disseminated for adoption in management decisions and policies (Chowdhury et al., 2021), particularly given the hyper-connectivity of our current societal and economic activities which can easily instigate future pandemics and associated anthropauses (de Senerpont Domis & Teurlincx, 2020).

While plenty of recent studies have hinted towards the pertinence of implementing the anthropause takeaways into management and policies, few elaborate on what specific lessons can be applied to urban water system management. In this section, we highlight six lessons for enhancing management of water systems with the sustainability principles of “ecological intactness” and “social relevance” (Smith et al., 2021) based on evidence from both COVID-19-era papers and our Dutch case study observations.

Working within a water system’s constraints is the first step in maintaining optimal human-ecosystem interactions. Therefore, defining ecosystem service operating and accessibility guidelines according to ecological needs (i.e. ecological intactness) as through a “services to ecosystems” approach (Comberti et al., 2015) can support management of human-ecosystem interactions. Three ecological-based takeaway lessons include the following:

4.1. Define recreational ecosystem service use thresholds

Boundaries for utilizing water systems can be set to avoid compromising vital functions or overtaxing uses. As our analysis of boating data showed, temporary cessation of boating can lead to fast changes in habitat. To foster these positive developments in water quality in the post-COVID-19 era, zoning canals to designate specific boating pathways can delineate areas for habitat and other water usage. In addition, limits can be placed on the number of people utilizing the system, such as with bathing areas having a maximum number of swimmers that can be present simultaneously and over the course of a time period.

4.2. Establish short-term anthropauses

As observed from the most restrictive periods of the anthropause, cessation of human interference permitted water system improvements (e.g. Loh et al., 2021). Enacting intermittent periods of restricted access after the pandemic could similarly promote periods for recovery, especially for vulnerable systems. For instance, no-boating periods in Amsterdam canals during spring vegetation growth periods can permit habitat establishment. Rotating access to bathing, fishing and scenic water systems can also decentralize recreational pressures for individual sites and mitigate synergistic pressures stemming from chronic system use (Sanjari et al., 2009). Further research will be needed to ascertain the duration of the improved ecosystem conditions and methods for maintaining the recovery after anthropauses end.

4.3. Continue scientific monitoring and (intersectoral) research

Despite the abrupt onset of COVID-19, existing ecological and social research programs, such as the Amsterdam canal water quality monitoring network and various citizen science projects, have supported knowledge-gathering even during society’s tumultuous adjustment period. Continuing to support scientific research and engaging with science-management intersectoral collaborations can safeguard knowledge production from future disruptions.

Fulfillment of water system uses for society’s needs (i.e. social relevance) is an additional aspect that has been affected by the anthropause. Here we reflect on three lessons for optimizing social investment in urbanized water systems:

4.4. Identify the (new) recreators

The anthropause may have bolstered recreator numbers as lockdown conditions permitted some individuals to have more time and opportunities to explore local natural spaces (Venter et al., 2020). Identifying which community demographics increased their use of nature during this time period and reviewing what systems were utilized (urban versus rural, green or blue spaces) could help develop management practices that foster the continued engagement of people with water ecosystems post-anthropause (de Senerpont Domis & Teurlincx, 2020).

4.5. Identify societal barriers to blue-green spaces

Blue-green spaces tend to be unequally distributed throughout urban communities, as was highlighted with COVID-19 lockdown restrictions (Pouso et al., 2021). Managing and creating these systems to be more accessible to all people can help bolster individual and community health (Venter et al., 2020). Conferring with marginalized groups about their experiences before and during the pandemic can help identify these accessibility issues and develop solutions (Dushkova et al., 2021).

4.6. Improve existing infrastructure

Existing and future water system infrastructure can be improved to sustainably accommodate more visitors. For instance, durable pathways can be installed to prevent erosion of paths (Bates et al., 2020). Mapping locations of frequent litter accumulations and installing refuse or recycling bins can help maintain the integrity of the water system and aesthetics of the surrounding area (Ammendolia et al., 2021). Building sanitation stations (hand sanitizer dispensers) to support hygiene during the pandemic and in e.g. influenza season can protect visitor health (Miller et al., 2021).

Of importance for all anthropause-derived management suggestions is the pace that knowledge is implemented. Under pandemic circumstances, numerous communities are aware of and invested in the value that the biosphere provides (Soga, 2021) and likely to be more receptive to management actions that support continued water functioning and service provisioning (Klenert et al., 2020). However, it is uncertain what proportion of nature enthusiasts will retain the same high regard and valuation of natural systems once other sources of recreation, wellness and businesses re-open (McGinlay et al., 2020). There are too many present-day drivers of ecosystem degradation to not leverage every opportunity for stimulating positive, informed and preemptive action (Strokal & Kroeze, 2020). Acting in the current pandemic window to maintain the remembrance of human and nature interconnectedness might have a good return on investment in establishing pertinent policies in the post-pandemic. Numerous institutions (IPCC, IPBES) and initiatives (UN Decade of Ecosystem Restoration) are similarly striving for a paradigm shift with water as a source of life, not just a resource to use (Seelen et al., 2019). Fostering a more eco-centric mindset in society going forward can subsequently promote prolonged and sustainable human-nature interactions, which will be paramount for handling climate change, extreme climatic events, societal evolution and future pandemics.

5. Conclusions

- Recent literature has demonstrated that human responses to the COVID-19 anthropause have had tremendous reach with implications extending to numerous sectors and systems, including aquatic ecosystems which are susceptible to anthropogenic pressures.
- Previously published studies illustrate that the effects of the anthropause (positive or negative) on water systems depended on a combination of the local health mandates (lockdowns, social distancing requirements), societal values (ecosystem service use and demand) and the water system itself (type, ecological health).
- Dutch urban water systems have experienced mixed effects on water uses during the anthropause that were linked to changes in ecosystem service accessibility and demand.
- Distilling the lessons from urban systems and implementing best practices during or soon after the pandemic can help retain society's positive perceptions and valuation of ecosystems, foster more environmentally conscious communities and establish environmentally-focused management practices.

Chapter Three -
Flipping Lakes: Explaining concepts of catchment-scale water management through a serious game

Armstrong, M., Kramer, L., de Senerpont Domis, L.N., van Wijk, D., Gsell, A.S., Mooij, W.M., and Teurlincx, S. (2021) Flipping Lakes: Explaining concepts of catchment-scale water management through a serious game. Published in Limnology and Oceanography: Methods, DOI: 10.1002/lom3.10436

OVERVIEW

Ongoing anthropogenic and climatic pressures on water systems have made water quality management a key challenge of the 21st century, reflected in legislation and policy such as the EU Water Framework Directive (2000), the US Clean Water Act (1972) and the Sustainable Development Goals (United Nations 2014). Water quality management is an interdisciplinary field, requiring knowledge of hydrology, ecology, governance, human behavior and economics. The challenges affecting lake water quality and the need for management on a catchment-scale are often hard to communicate to a wider audience of non-water professionals. As catchments can span large parts of regions, these hydrologically-delineated areas are often too large for people to directly associate with their own living environment (Koroleva and Novak 2020). Processes that take place over decadal time scales as well as across large spatial scales may be difficult for people to grasp intuitively (e.g. climate change, critical state shifts in lakes due to eutrophication) or to visualize (e.g. loading from point and diffuse pollution sources) (see Seelen et al. 2019a). For example, the impacts of a gradual increase in temperature due to climate change (Adrian et al. 2009) or the accumulation of pollutants over time in downstream lakes and river reaches (Teurlincx et al. 2019) may feel intangible to audiences. Communicating clearly about these challenges, particularly with non-water professionals, is crucial in order to achieve a holistic approach to addressing catchment-level pressures on lake ecosystems.

Improving the environmental literacy of stakeholders regarding lake management, ecology and eutrophication concepts can aid in engaging them in management discussions. For instance, with heightened stakeholder understanding of how pressures are affecting local lake systems and the wider catchment, discussions about solutions can be facilitated. Well-informed and environmentally literate communities can aid management by integrating their local knowledge into management actions (i.e. co-design), thereby improving the effectiveness of management plans (Robertson and McGee 2003). In some cases, informed stakeholders can also assist with mobilizing social support for enacting effective management actions that are costly or require community participation (Cooper et al. 2007; Franzen et al. 2015). The communication of catchment-level water quality management intricacies is a first, necessary step for creating a holistic management approach.

Applying game approaches to explain complex and discipline-specific concepts can improve knowledge accessibility by making the material more tangible, comprehensible and simplified (Susi et al. 2007). Therefore, the use of games or game elements can be suitable to begin addressing the challenges of catchment-level water quality management (Albertarelli et al. 2018). Examples of effective game or game-element applications include classroom lessons (Boskic and Hu 2015), multi-stakeholder discussions (Medema et al. 2016), citizen-science projects (Eveleigh et al. 2013; Seelen et al. 2019b) and more. Serious games, which are defined as “games that are used for purposes other than mere entertainment” (Susi et al. 2007), have entered a wide range of scientific fields as a method for communicating complex concepts. The application of serious games into environmental sciences in particular has proven useful in education and engagement of non-expert audiences (Madani et al. 2017). As the scales of environmental processes range from microscopic to global, it can be a challenge for individuals untrained in the research topic to visualize and therefore understand these processes. Presenting a concept within a set playing field with specific rules and a defined goal can engage audiences with their existing problem-solving skill set (Landers 2014).

Following the serious game approach, we have developed “Flipping Lakes.” This game, with an underpinning in ecological knowledge and theory, is intended to facilitate outreach and education of catchment-scale water quality management. The game uses both simplified system processes and a customizable catchment structure to support its application as an effective water quality and ecology communication tool to a varied audience. We tested the efficacy of Flipping Lakes as a teaching tool with groups of students, lake scientists and the broader public. Based on our findings, we developed best practices for gameplay and offer an outlook to future applications of the game.

MATERIALS AND PROCEDURES

Flipping Lakes is a serious game about eutrophication prevention and management at the catchment-scale. The game takes place within a customizable fictitious catchment that is constructed with the placement of the game's catchment cards on a table or similar playing surface. Nutrient pollution (i.e. excessive nutrients) is generated by catchment cards and transported from sources in the catchment towards a downstream focal lake. Players take on the role of water managers and are tasked with protecting the ecosystem services of this downstream focal lake (e.g. recreation, biodiversity). Introduction of pollution into any lake present in the game can cause its clear state to shift to a turbid state. During each turn, which represents one year in the game, players can carry out management actions throughout the catchment that are aimed at either stopping the impacts of pollution (adaptation measures) or reducing pollution sources (mitigation measures). These management actions have to be bought with "Aquabucks," which represent the allotment of public money for water management. A share of Aquabucks becomes available at each turn. Typical gameplay lasts for 15 turns, with pollution being transported through the catchment during each turn, and management actions implemented with the available Aquabucks. Failure to protect the focal lake situated at the downstream end of the catchment from the pollution will result in it flipping from a pristine (i.e. clear) to a deteriorated (i.e. turbid) state and the players losing the game. This game targets a wide audience, including a range of professional disciplines and ages (10+), as most people have some interest or investment in water quality (see Seelen et al. 2019a). The game is designed to educate citizens and students on catchment management and to facilitate intersectoral discussions among water professionals and other stakeholders.

Scientific underpinning of the game

Flipping Lakes has its scientific basis in limnological theory. Regime shifts are a core concept in limnology, made famous in shallow lakes theory (Scheffer and van Nes 2007) where lakes go from clear, submerged macrophyte-dominated states to turbid, phytoplankton-dominated ones, or vice versa (van Nes et al. 2007; Janse et al. 2008). An important aspect of such regime shifts is the existence of hysteresis (van Nes et al. 2007), indicating the need for reducing nutrient loads far beyond the level at which the lake originally underwent a regime shift to a turbid state in order to return to a clear state. Similar ecological regime shifts driven by nutrient dynamics have also been described for deep lakes, revolving around phosphorus supply and hypolimnetic anoxia (Carpenter and Cottingham 1997). Lake ecological states and their resulting ecosystem services, especially in terms of nutrient retention, are also an important part of the inspiration for Flipping Lakes.

Lakes can serve as a net nutrient source (i.e. lower inflowing relative to outflowing nutrient load) or a net sink of nutrients (i.e. higher inflowing relative to outflowing nutrient load) in the catchment. There is evidence for increased retention of nutrients in submerged plant dominated systems compared to phytoplankton dominated ones (Hilt et al. 2017; Janssen et al.

2020). Furthermore, the water purification capacity (i.e. phytoremediation) of aquatic plants has long been acknowledged in scientific literature (Truu et al. 2015; Janssen et al. 2020). Phytoplankton, in contrast to macrophytes, are easily transported along with the water flow (Elliott 2010; Teurlincx et al. 2019), thereby transporting nutrients downstream. In addition, the nutrient legacy stored in many lake sediments due to decades of excessive nutrient loads (Søndergaard et al. 2003) can serve as a source of nutrient pollution from turbid lakes, a problem that is hampering the recovery of many lakes even when external loads are reduced (Zamparas and Zacharias 2014). Within the game context, the role of a lake as a definitive source or sink is intentionally oversimplified for ease of gameplay. The capacity of lakes to retain or release nutrients is reflected in the clear and turbid states which lake catchment cards can flip between.

Regime shifts can lead to cascading effects in connected lake systems (Hilt et al. 2011). For instance, there can be a cascading effect where a lake undergoing a regime shift into a turbid state can lead to an increase in nutrients which travel downstream, causing the receiving lake to undergo a regime shift due to the increased nutrient loading (Teurlincx et al. 2019). Managing systems for maximal nutrient retention has the potential to cause the inverse of this cascading effect, where the retention capacity in upstream systems helps to preserve water quality of downstream systems (Jarvie et al. 2013; van Wijk et al. 2021). These spatial cascading effects are represented in Flipping Lakes through the interactions among lakes within the catchment.

Specifics of gameplay

In this section we first introduce the different game pieces that comprise the game and their purpose. Following this, we describe the overall progression of a game session in detail.

Nutrient pollution

Within the context of Flipping Lakes, players are challenged with managing the amount of nutrient pollution that is entering the catchment area and the impacts it has on lake water quality. Within the context of the game, the term “pollution” is specifically used to describe nutrient pollution (i.e. eutrophication), or the excess input of nutrients (both in dissolved and particulate form) that originate from sources throughout the catchment. Pollution is deemed to be a more accessible term than “nutrient pollution” or eutrophication, therefore making it easier to engage a wide audience and avoiding discussions regarding the need for some nutrients in water for a healthy ecosystem. Hence, from here on, the terms “pollution,” “pollution removal” and “pollution load” will be used to refer to, respectively, nutrient pollution, nutrient retention and nutrient loading.

Catchment design

The game board consists of three types of cards: lakes, pollution sources and waterways (connection cards). The game board always contains at least one focal lake, which is situated downstream, and an inflow point at the upstream end of the catchment. All other cards in between the inflow and the focal lake are entirely customizable. Therefore, the catchment can be designed to suit the needs of the user, such as by making it fit to an existing catchment or by emphasizing the presence of a specific pollution source in the game catchment.

Lakes

Lake cards are two-sided with one side representing a turbid system state and the other a clear system state (Figure 1). The turbid state of the lake cards emulate internal loading processes (Søndergaard et al. 2003) by being a source of pollution within the game’s catchment. Each card states the amount of pollution that the lake will add to the catchment each turn while the card is in the turbid state. In contrast, the clear state of the lake card acts as a sink of pollution within the catchment with its simulation of a lake's nutrient retention capacity (Jeppesen et al. 2011). Lakes in the clear state can assist with the management goal through the retention of nutrients in the lake sediment. In the game, this function of a clear lake will permanently remove a limited amount of pollution pieces from the card, and therefore from the catchment, every turn.

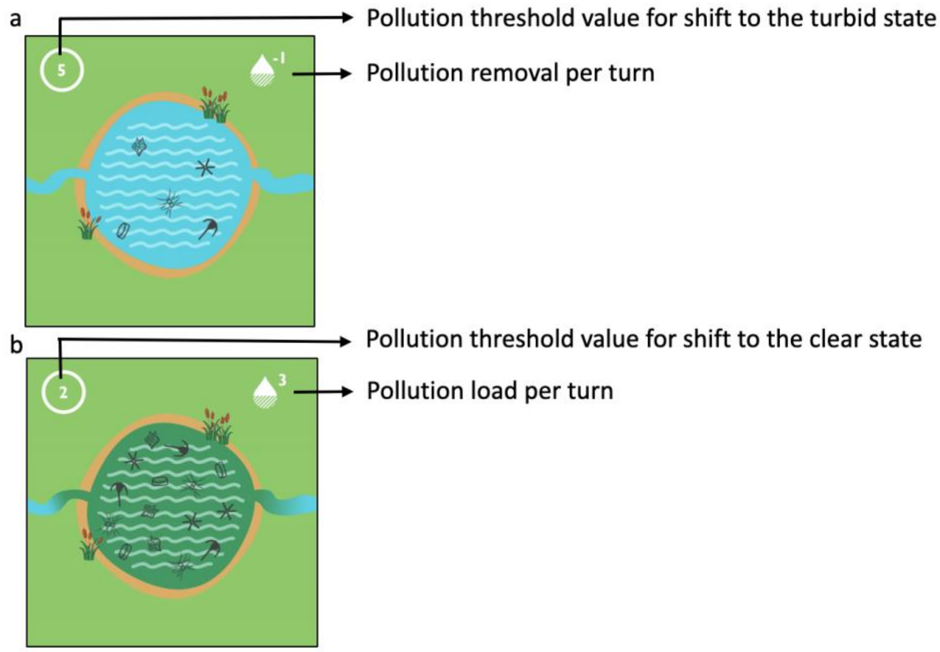


Figure 1: Example lake catchment cards with the lake card's clear state (1a) including the pollution threshold value and pollution removal value and the lake card's turbid state (1b) including the pollution threshold value and pollution loading amount.

The lake cards within the catchment are dynamic over the course of gameplay as a lake may flip over into the alternate state depending on the amount of pollution pieces located on the card during a given turn. The number of pollution pieces that will result in a flip from one state to another are displayed on the card. Players can alter the lake state by implementing various management measures on the card itself or elsewhere in the fictitious catchment. Strategic decisions can be made that will either decrease pollution to a level that allows the turbid lake to change into its clear state, or to ensure that a lake stays in the clear state by remaining under the provided "flip" pollution threshold value (i.e. the lake critical nutrient limit, critical nutrient loading or lake resilience to a state shift; Scheffer and van Nes 2007; van Nes et al. 2007). As multiple lakes can be part of the game board, managing them effectively is a key aspect to achieving the goal of the game.

The main goal of the game is to keep the focal lake from flipping over into the card's turbid state. In general, this lake system is sensitive to pollution inputs as even small quantities can reduce the provisioning of lake ecosystem services that are desired by the fictitious community. The flipping over of the focal lake from clear to turbid denotes the end of the game.

Pollution sources

In addition to the nutrients released from the turbid state of the lake cards, there are other sources of pollution within the game's catchment. Cards representing upstream reaches, agricultural areas, urban areas and sewage overflows serve as structural sources of pollution to the water system. These cards are characterized by a pollution load value (1 to 10), which dictates how much pollution is added to the card, and ultimately into the catchment (Figure 2). Pollution from the various sources is added every turn as a simulation of the continuous production and release of pollution through time (Greene et al. 2011). While the addition of a single unit of pollution to the catchment is unlikely to pose an immediate problem, there can be complications from the accumulation of pollution through time and by the movement of pollution along the catchment cards. The sewage overflow card is a special case as this card only delivers a point-source pollution load into the catchment during the *Extreme rainfall event* scenario (see "Event scenarios"). These pollution source cards can be deliberately chosen and placed within the game playing field to depict a specific catchment system. Conversely, these cards can be randomly selected and distributed within the playing field. Between the type of pollution cards chosen, the number of cards introduced to the playing field, the placement within the playing field and the card's pollution load value, the resulting catchment can offer abundant variability in the scenario which players must manage.

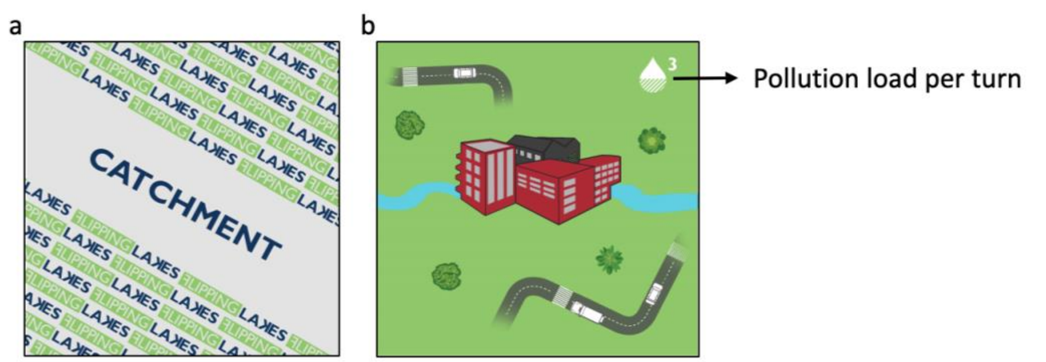


Figure 2: Example pollution catchment card with the card back (2a) and the gameboard side (2b) containing the pollution load value and two river connections.

Spatial connections

Cards representing waterways are used to connect pollution sources and lakes into a catchment network. The purpose of the waterways in the game is to transfer pollution through the catchment. In contrast to the lake cards with their dynamic system states, the spatial connection cards act as pollution transferral pathways regardless of the amount of pollution on a card at any given time.

Event scenarios

Flipping Lakes was constructed to have various scenarios that players have to manage. An event card (Figure 3) is revealed at the start of each turn and can influence the rules of the game for that turn of the game. There are seven types of event cards. The *Business-as-usual* scenario is typically the most common event and does not affect the rules of engagement for Flipping Lakes during that turn. The other six types are based on societal events and climatic events (Table 1). Compared to the complex impacts that these events can have on real-world catchments, the implications of these events in the context of the game are simplified in order to demonstrate how the compounding of pressures across turns can impede achievement of management goals. Presenting players with these events throughout the gameplay causes additional hurdles for management which can directly impact how players react during that turn. Additionally, the repercussions of these events could be long-lasting, requiring additional management measures over the course of a number of turns to address the impact of the event.

Table 1. Overview of Flipping Lakes events

Event type	**Event card**	**Impact**
Climatic	Heatwave	Multiply all pollution added this turn by 1.5
	Extreme rainfall	Pollution travels two catchment cards this turn, also over dams
	Extreme drought	Pollution does not travel this turn
Societal	Agricultural intensification	Agricultural catchment cards produce +1 pollution from now on
	Feeding ducks	One lake is flipped over to a turbid state
	Dog park construction	Adds a +1 pollution source to the catchment

Societal events

Anthropogenic actions have the potential to shape and significantly alter the catchment landscape (Rashid et al. 2012). To represent the influence of such actions, this game has event cards related to the human actions and interventions of *Agricultural intensification*, *Feeding ducks*, and construction of a *Dog Park* (Table 1). All of these event cards directly influence the amount of pollution that enters into the catchment system each turn. In the absence of management measures, these events will be an additional and permanent source of pollution to the catchment.

Climatic events

Extreme climatic events, or weather events that lie on the extreme ends of the climate spectrum, are anticipated to become more intense and frequent with the continued trend of climate change (Seneviratne et al. 2012). The extreme event cards of *Heatwave*, *Extreme rainfall* and *Extreme drought* (Table 1) present simplified scenarios in which the climate can impact lakes and catchments. These events have implications on the game catchment in two ways. First, the *Extreme rainfall* and *Extreme drought* events alter water movement and thereby pollution transport through the system during that turn. Such changing flows of pollution can be both a hindrance or a help to the player. An example of this is the *Extreme rainfall* event which causes pollution to move two spaces over the course of one turn. This can hinder the player by speeding up the flow of pollution to their focal lake. However, it may also push the pollution that is flowing through a lake card into a subsequent waterway, thereby avoiding the lake card from flipping from a clear state to a turbid state (i.e. a flushing event). The underlying idea of these events is that they can temporarily change the rules of the game, much like climate change is doing for ecosystems in the real world. Second, the *Heatwave* event, and the *Extreme rainfall* event can increase the amount of pollution added during that turn. The severity of all events are context dependent, with effects varying depending on the catchment configuration (amount of loading sources, presence of sewage overflows), the current state of pollution and the previous management actions taken by the player.

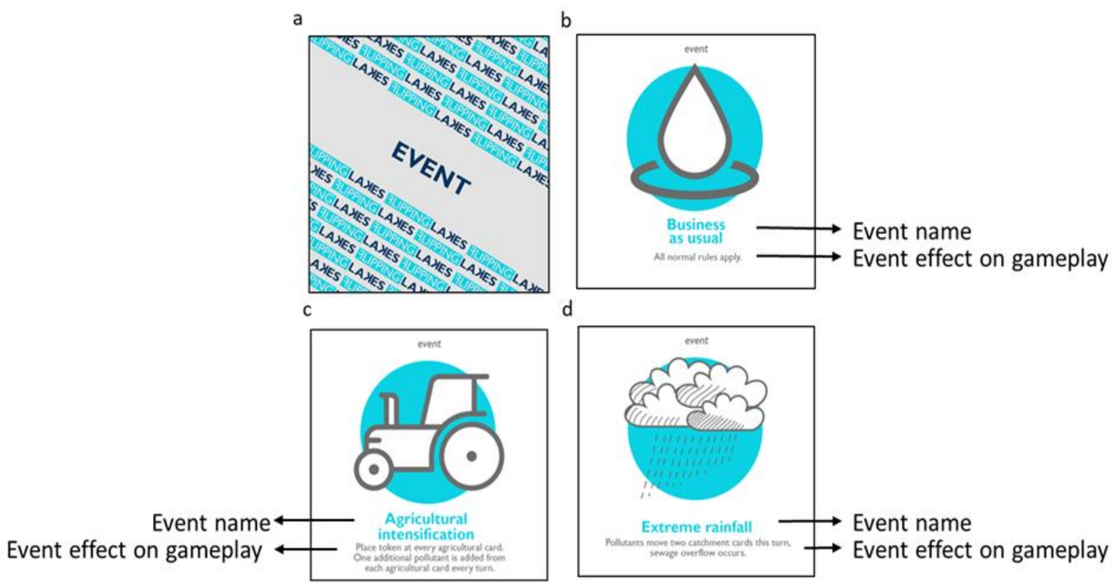


Figure 3: Example event card with card back (3a) and front (3b-d) containing explanation of the scenario effect on gameplay for a *Business-as-usual*, *Agricultural Intensification* (societal event) and *Extreme rainfall* (climatic event) scenario.

Management measures

The primary method to influence the outcome of the game is applying management measures (Figure 4). During each turn, players receive a specified amount of the fictitious currency Aquabucks to spend on different measures, either during that turn or in subsequent turns. The costs of the measures were purposely expressed in a fictive currency as to avoid direct association to real world monetary costs. Rather, prices of measures were scaled only to have some reflection of expensive versus inexpensive approaches. There are nine options for managing the pollution sources and stressors within the catchment (Table 2). These measures can be used to mitigate pollution loads or to adapt the catchment when dealing with pollution.

Table 2. Overview of Flipping Lakes management measures

Management type	**Measure card**	**Impact**
Mitigation	Agricultural legislation	Agricultural card produces 1 pollution every turn from now on
	Increase public awareness	Pollution is reduced by 1 from now on
	Sediment capping	Turbid pollution production is prevented on the lake card
	Increase water storage capacity	Pollution is retained for an extra turn
Adaptation	Water treatment plant	Up to 8 pollution is removed from the card each turn
	Bank filtration	Up to 1 pollution is removed from the card each turn
	Dredging	All pollution is removed from the lake card
	Dams	Pollution movement is prevented
	Increase water storage capacity	Sewage overflow from the extreme precipitation event is prevented
Foreknowledge	Predictive model	Preview the event scenario for next turn

Mitigation measures

Several measures are aimed at directly addressing the pollution source(s) within the catchment setting. These types of mitigation measures reduce or prevent the entrance of pollution into the water system, thereby taking action to solve the problem underlying the ecosystem's health. Within Flipping Lakes, there are three ways in which mitigation measures can influence gameplay. First, anthropogenic practices can be made more sustainable. In the game, this can be done by applying the management actions of *Agricultural legislation* or *Increase public awareness*. Second, nutrient loading from the sediment of a turbid lake into the water column can be halted with *Sediment capping*. Last, prevention of sewage overflow pollution entering the catchment can occur when the measure *Increase water storage capacity* is applied to the sewage overflow catchment card.

Adaptation measures

Adaptation measure options are built into Flipping Lakes as a method for dealing with the impacts of pollution once it is already in the catchment. Site-specific pollution treatment can be implemented by construction of a *Water treatment plant* and with the establishment of *Bank filtration*, both options permanently remove a limited amount of pollution from the catchment. Pollution located on a catchment card can also be removed directly through *Dredging* of the sediment, causing the removal of all pollution present on the card during the turn in which it is used. *Dredging* is a one-time measure, in contrast to the pollution treatment measures (*Bank filtration*, *Water treatment plant)* which last throughout the game. Water flow can be manipulated by constructing *Dams* within the catchment impeding the movement of pollution in the catchment under most circumstances of gameplay. Using the *Increase water storage capacity* anywhere on the catchment except for sewage overflows (see above) allows it to be used as an adaptation measure to temporarily keep pollution in place.

Foreknowledge

Players can benefit from foreknowledge gained through playing the *Predictive model* card. This measure allows players to see the event card for the next turn, providing an opportunity to adapt their strategy to the impending pollution sources and movement thereof.

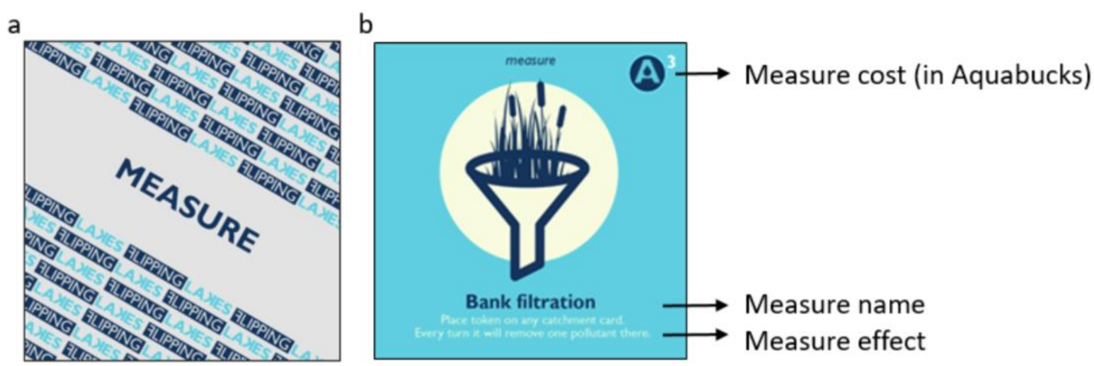


Figure 4: Example management measure with card back (4a) and front (4b) containing explanation of the card effect on gameplay and cost of the measure.

Playing the game

A game moderator can direct the players in the aspects of gameplay by first creating the board lay-out and choosing the types and order of events that are appropriate for the session at the start of the game. The players may be given an overview of the measures that can be implemented during the game play and the impacts that the various events could have. Flipping Lakes games are typically run for 15 turns. The scenario card is revealed at the start of each turn. This event scenario will dictate whether special rules are applied to the gameplay during that turn (see Table 1). The player or group of players will receive an allotment of Aquabucks as a representation of public money available for management actions. The players then have an opportunity to consider, pay for and enact one or more of the management actions (see Table 2). Purchased measures are implemented immediately within the catchment. Next, pollution is added into the catchment according to the sources present on the board and as indicated by the event scenario. There are opportunities to remove pollution from the catchment cards if there is a purifying effect, such as with clear lake cards, helophyte filters (i.e. *Bank filtration*) and mechanical water treatment (i.e. *Water treatment plants*). Pollution then moves downstream along the catchment cards towards the focal lake (at a pace of one catchment card per turn under *Business-as-usual* scenario). At the end of each turn, players review the current status of pollution in their catchment area and flip lake cards to the turbid state if the amount of pollution exceeds the pollution threshold value or to the clear state if pollution is below the given threshold value. If the focal lake has not exceeded the pollution threshold and therefore remains in the clear state, players have successfully managed the catchment for that turn and may proceed with the next turn. Players have won the game when they keep the focal lake in pristine condition until the end of the 15th turn (a detailed game manual is supplied in Appendix 1).

Availability

Flipping Lakes is an open communication tool under a Creative Commons license (CC-BY-NC-SA). The game will be made available upon publication at www.nioo.knaw.nl/flippinglakes and www.nioo.knaw.nl/en/flippinglakes. Game instructions and all materials are provided on the website. An explanatory video and other supporting materials will also be available for learning about and applying this communication tool.

ASSESSMENT

Methodology for assessing the impact of Flipping Lakes

Flipping Lakes has been introduced to a diverse range of players through trial runs in Europe, Asia and North America (as shown in Table 3). On these different occasions, players were asked for their opinion on whether they learned something by playing the game or not. Below, we describe the qualitative impressions from various groups as expressed by the game moderators (authors of this paper). An opportunity to ask for anonymous feedback on the usefulness of the Flipping Lakes game for broader application by water professionals presented itself at the Global Lake Ecological Observatory Network All Hands' Meeting in Huntsville, Canada (GLEON 21; Figure 5). During this meeting, professional and student members of lake science and associated disciplines along with local lake managers could play Flipping Lakes as a team. Meanwhile, observers and participants were given the option to provide anonymous feedback on the game and its usefulness for communication, education, and public outreach purposes through a survey form on a standard laptop of one of the game moderators.

Figure 5: Photograph showing a game of the Flipping Lakes game being played at the GLEON 21.5 All Hands' Meeting in Huntsville, Canada.

We also tested the application of Flipping Lakes in an academic setting with bachelor students from Utrecht University participating in an Aquatic Ecology course. During this course, we measured perceived comprehension of select lake science concepts (see Appendix 2) by having students self-score their familiarity of the concepts on a scale from 0 (not familiar) to 10 (expert) prior to playing the game. Each student re-scored their familiarity of the same concepts after playing the game two to three times in groups of 4 students under the supervision of a game moderator. The scoring was carried out anonymously on a standardized scoring sheet which was printed on both sides, guaranteeing that participant results remained paired. Students provided their explicit permission for using the data for scientific publication through completion of an online survey form (Appendix 3). The results of the students' scores were analyzed using a paired Two-sample Fisher-Pitman permutation test (R package coin; Hothorn et al. 2019). We analyzed the results both by grouping all the lake concepts together, and by looking at each of the concepts separately.

General reception of Flipping Lakes by diverse user groups

Reception by professional water managers

Flipping Lakes was introduced to professional water managers at the Dutch water management agency Hoogheemraadschap van Schieland en de Krimpenerwaard (HHSK).

During this introduction, the catchment was modeled after part of the urban water system of the city of Rotterdam, the Netherlands. The game received positive responses with immediate outlooks to using it as a tool for simple scenario demonstrations for local water system restoration projects. The water management professionals also indicated their desire to own a set of the game for outreach events.

Reception by the general public

Flipping Lakes was used as an educational tool to facilitate public outreach through moderated sessions. We used the game at an open day at the Netherlands Institute of Ecology (attended by over 1600 people of diverse demographics). At this event we used the game in a demonstration format to discuss water quality concepts and challenges with approximately 150 people, of whom 29 decided to play a full game with a game moderator.

Reception by university students and administration staff

The game was also used for outreach with the academic and administrative staff of the School of Business at Erasmus University Rotterdam during the “Blue Monday” event. Players showed an understanding of the underlying societal and ecological logic of Flipping Lakes with improved comprehension of cause effect-chains of measures and pollution reduction over the course of the gameplay. Additionally, we observed that the game's interactive nature helped ease player participation in discussing the fate of pollution within the catchment system, implications of degrading lake ecosystems and strategies for reducing pollution. This allowed the game moderators to discuss and explain some of the more difficult concepts in catchment management and lake ecology (e.g. point vs. diffuse pollution, hysteresis of lake ecosystems, adaptive vs. mitigative measures).

The game was also used within an introductory course on aquatic ecology for Master and PhD students in civil engineering and microbial ecology disciplines at the Yangzhou University in China. Here, the lecturer gave students a hands-on review experience of the course lecture materials by using Flipping Lakes as a visual and interactive tool. Upon finishing the game, the players informally reported that the game helped them to better understand the consequences of connectivity in water systems for the accumulation of pollution over time and space.

Quantifying the usefulness to water professionals

Ten water professionals at the Global Lake Ecological Observatory Network All Hands’ Meeting (GLEON 21) provided feedback on their experience with the game. On average they rated the usefulness of the game for communication and education purposes at 9.1 out of 10 (min: 8, max: 10). Further, respondents thought that this game was suitable for use with students (90%), communicating to local general public (90%), and communicating with local stakeholders (60%). A main conclusion of the event was that there was a high potential application of the serious game in an educational context.

Table 3. Flipping Lakes trial runs

Purpose	Audience	Occasion	Location	Country
Communication	Water managers	Innovation fair	Hoogheemraadschap van Schieland en de Krimpenerwaard	the Netherlands
Community interest, scientific communication	Water professionals	GLEON 21 All-Hands' Meeting	Huntsville	Canada
Education	Faculty & administration staff	"Blue Monday" event	Erasmus University Rotterdam	the Netherlands
Education	Master & PhD students	Masters course	Yangzhou University	People's Republic of China
Education	Bachelor students	Bachelor's course	Utrecht University	the Netherlands
Public outreach	General audience	NIOO Open Day	Netherlands Institute of Ecology	the Netherlands

Perceived learning of water quality concepts through Flipping Lakes

Perceived learning outcomes of the bachelor course students (n=12) for different concepts encompassed by Flipping Lakes showed an overall positive result (Figure 6). 19 out of 20 concepts showed a significant improvement in perceived knowledge post-gameplay (Appendix 4). The overall results show that, with the exception of the concept of pollution impacts ($p<0.1$), there was a significant increase in perceived knowledge of the concepts after playing the game (Figure 6, Appendix 4). The paired data points of individual students are based on their self-reflection of concept familiarity, opening up the possibility of opinion and personal beliefs to influence the scores. For instance, the knowledge and professional experiences that students had prior to participating in the serious game session can influence the value of the numeric scores reported in the pre-game survey. It is therefore likely that a diverse class can have a range of values on the scale of 0 to 10 for the pre-game scores. The scores reported following gameplay will similarly be subject to each individual's perception of their previous knowledge, of their experience with the serious game and of how they quantify that difference. It is the overall trend of improvement throughout the student data that supports the notion that important concepts behind catchment-scale management are elucidated by playing the Flipping Lakes serious game (see Appendix 4 for results per concept).

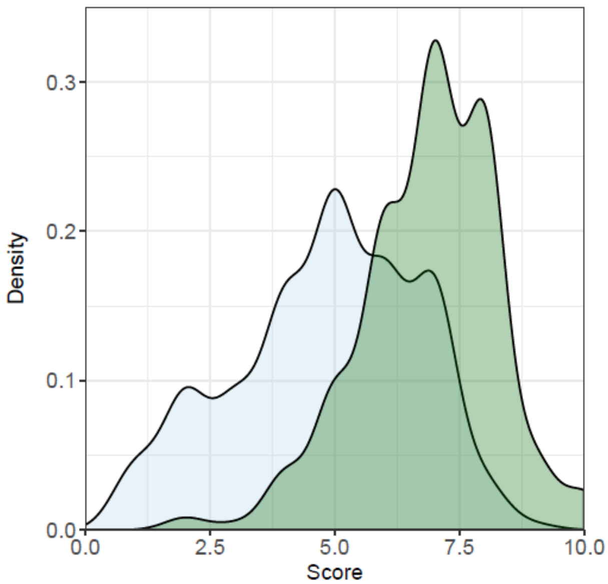


Figure 6. Overall level of perceived concept knowledge (n=12) before playing Flipping Lakes (light blue) and after (dark green). The scores (x-axis) range between 0 (not familiar with the concept) to 10 (expert on the concept) and the y axis gives the cumulative probability density (fraction of participants) based on the kernel density estimation method of Sheather and Jones (1991).

DISCUSSION

The need for catchment-level management is widely accepted (Falkenmark 2004; Hughes and Quinn 2014). Establishing a holistic approach to system management requires the active engagement of lake stakeholders and users in the conversation around lake pressures and management thereof. To support these groups, insight about the types of challenges that are occurring, the pressures that are impacting the catchment system and the different management options must be communicated. As the role of serious games as a tool to aid stakeholder engagement with the game's topic is increasingly recognized (Rumeser and Emsley 2019), Flipping Lakes can assist in increasing players' comprehension of catchment-level ecological and management concepts within a game setting. Moreover, engaging players with complex topics through boundary objects such as serious games can help lower communication barriers and cross intersectoral boundaries. Through enhancing the environmental literacy of stakeholders and lake users, the first step towards holistic and inclusive decision-making can be achieved (Larson et al. 2015; Jean et al. 2018). Here, we have shown that a diverse group of players from the limnological community sees potential for the Flipping Lakes game as a communication tool, and that it can facilitate education of scientific and management concepts (Figure 6).

A plethora of other serious games already exist that tackle some of the subject matter present within Flipping Lakes (see e.g. Shapiro and Squire 2011 for some examples "Citizen Science" and "Trails Forward"). We argue that the diversity of serious games focusing on water management should be valued, much as we value biodiversity for filling niches in a physical environment (see Janssen et al. 2015 for a similar argument with respect to aquatic ecosystem model diversity). Each game has its own unique merits that can fulfill a role in expressing environmental concepts with their different focuses on certain limnological concepts and with their own gameplay mechanics. Flipping Lakes with its unique set of design principles serves to expand the diversity of serious games available to the limnological community as a whole. With the addition of another tool to the toolbox of scientists and water professionals to engage and educate other stakeholders, the capacity to co-design watershed management plans across knowledge boundaries (see Jean et al. 2018) is closer to becoming a reality.

Flipping Lakes distinguishes itself from existing serious games on catchment-scale water management through its core design principles as well as its scientific basis. This game's first core design principle is the medium through which the game is played. A number of recent serious games within the discipline of limnology are web-based virtual games (see e.g. Gaydos and Squire 2012). In contrast, Flipping Lakes is played with a physical board, cards and game pieces. With a table-top approach, this game promotes real-time and collaborative interactions between players and moderators (Castronova and Knowles 2015). While video games can support this same experience to an extent when the game is based on real-time team play (see e.g. Wendel et al. 2013), aspects of the discussion can be lost through a virtual interface. The face-to-face promotive interactions of board games (such as Flipping Lakes) are known to support collaborative learning (Kristiansen et al. 2019) as they allow players to directly help, assist, support, encourage and praise the success of other participants (Johnson and Johnson 1999).

The second core design principle of the game is its fully customizable nature. This game's design is intended to allow for the widespread application across cultural and social boundaries (Jean et al. 2018). The flexibility of the game allows participants to have a continually shifting and enriching experience enacting management decision-making in different catchments with various combinations of pressures. Paired with the freedom to choose which events will occur throughout the duration of gameplay, there are multitudes of scenario combinations that individual players and teams can experience. Flipping Lakes can be structured to facilitate scenarios ranging from purely fictitious situations up to simulating a real catchment area with semi-realistic climatic or societal-based scenarios.

The third core design principle of the game was to remove barriers for potential users to access and apply the tool. Accessibility of serious games is an important aspect in determining their uptake by students (Tsekleves et al. 2014). We ensure wide access by making the game materials openly and freely accessible through the Flipping Lakes webpage (www.nioo.knaw.nl/flippinglakes). All of the cards, pieces and instructions required for gameplay are provided in an easily printable format, allowing potential users to print the game themselves. We thereby remove paywalls (e.g. shipping costs) and minimize the technological structure necessary for acquiring a physical copy of the game. The added advantage is that unique game sets can be made that are collated for individual game play needs. This can be done by printing out different quantities of the game pieces associated with the catchment, events and measures. Also, we actively encourage the community to expand the game cards to suit their own purposes and share such work through the Flipping Lakes webpage.

While serious games are frequently referenced as relevant for education, communication and facilitating discussions (Jean et al. 2018), reports on their application in real world settings is limited. Especially reports of quantitative assessments on the efficacy of these tools are seldom presented in literature. For Flipping Lakes, we have carried out both qualitative explorations of its reception as well as a small quantitative assessment with 12 students. This quantitative assessment clearly illustrated the usefulness of the game as a communication and education tool, despite its low sample size. Nonetheless, future applications will need to show its applicability with other stakeholder groups and for other purposes such as facilitating co-design of management plans. We see a role here for the community of users and facilitate them to supply both qualitative and quantitative feedback to us and each other through the Flipping Lakes webpage (www.nioo.knaw.nl/flippinglakes).

The scientific basis underlying Flipping Lakes has a strong focus on lake ecological processes and functioning. Other serious games exist that have included ecology as a concept of their gameplay in some shape or form (see e.g. Mathevet et al. 2007; van Hardeveld et al. 2020), though often it serves as an end result of actions taken by the player. Flipping Lakes is one of a small number of serious games where the ecological functioning of the lake systems directly impacts the game's outcome, making ecological recovery of lake systems a means to reach the goal of the game rather than the goal itself. Ergo, Flipping Lakes makes a much needed contribution to the existing set of serious games by incorporating lake ecology as a guiding theme (see chart in Madani et al. 2017).

Through the unique combination of the above described design principles encompassed by Flipping Lakes, we aim to contribute to the improvement of scientific literacy of a wide audience regarding limnology, ecology and water management.

COMMENTS AND RECOMMENDATIONS

Based on the experience of moderating and playing Flipping Lakes ourselves, we have formulated a number of recommendations for gameplay and for future development:

Recommendations for first time players

When introducing Flipping Lakes to first time players, it is recommended to create a set-up that promotes learning of the game rules and that safeguards players from losing the game during this learning period. is Therefore, the first step of supporting comprehension of the game without overwhelming players is constructing a board in a configuration with minimal pollution sources. In practice this could be including one agricultural card and one urban card in the catchment. Similarly, having one or more of the non-focal lakes embedded in the catchment start in their clear state will offer both a buffer against the pollution while players figure out the management actions options and simultaneously offer a discussion point regarding the stable alternative states of the lakes. Ensuring that three consecutive connection cards are located between the focal lake and the closest source of pollution will also assist with the simplified set-up. We recommend that the first three turns of the game will be *Business-as-usual* events, paired with a simple catchment system. This effectively permits players to become familiar with the basic rules of engagement that occur each turn and with how the various aspects of the game interact to create the management challenge.

Recommendations for advanced players

Conversely, when players are familiar with the Flipping Lakes game, additional rules can be added in order to increase the difficulty of the game or to more realistically reflect existing management challenges. Modifications of the game can occur with the board configuration, the events, the management measures options and the Aquabucks allotment. The board can be configured in a number of ways in order to increase the challenge. Three of these methods include 1) increasing or randomly selecting the number or type of pollution cards within the catchment (e.g. agricultural and urban cards), 2) starting the non-focal lakes in a turbid state, and 3) having two or more recreational lakes in the system. By randomizing the catchment cards in play, the chances of having a catchment setup that is (near) impossible to manage successfully increase. While this may disappoint players, it can serve as a great example of how past landscape geographical design choices can lead to nearly unmanageable catchment systems. Furthermore, Event cards can be customized to reflect different future scenarios. To introduce players to the difficulties of management in a changing world we recommend that players go through two play-throughs of the game on the same catchment. The first play-through has a mixture of event cards with half of the set being *Business-as-usual*. In the second play-through, the event cards could be ordered to have more societal events or climatic events to demonstrate scenarios with more human intervention and climate change pressures, respectively. Communicating the importance of climate variability for managing lakes (Havens et al. 2016) can be attained through smart stacking of the event card deck with climatic events combined with random shuffling of the deck between two games. While Flipping Lakes is unlikely to reflect real world climatic variability, randomizing the climatic events has the potential to illustrate the difficulties of managing a catchment in a stochastic world. Furthermore, the availability of management measures options could be adjusted either before the game begins or in the middle of gameplay. Removing some of these options will force players to adjust previous approaches to address the pollution situation or to develop entirely new strategies. If this is done in combination with stacking specific event card types, the management scenario can reflect real-world situations and restrictions due to policy changes (e.g. Downing et al. 2014). Finally, the amount of Aquabucks that the player or team receives each turn could be adjusted at the start of the game or in the middle of gameplay. Such a scenario can reflect changes in governance with relation to the funding for water management. The limitation of funds can force players to reconsider which management actions should be implemented, when they should be done and where in the catchment they would have the most impact. An extreme case of funding insecurity could be introduced by letting players roll a six-sided dice to determine the amount of Aquabucks that they receive each turn.

Recommendations for game moderators

When applying the game as a learning tool, having a game moderator that can build, run and explain the game will help enrich player understanding of the underlying game concepts. For instance, moderators can provide varying degrees of explanations regarding the water quality management concepts that are tailored to the player background knowledge, educational level (e.g. elementary school player versus university student player) and interest levels. When moderating games, it was found that player teams consisting of two to five people were optimal. Larger groups are also possible, though the trade-off can be the reduced capacity of the moderator to facilitate discussions and answer questions. Additionally, a longer time frame is usually needed for larger groups to provide sufficient time for the deliberation of management actions and strategies each turn. In the event that a game moderator is leading a group of 6 or more players, a more stringent approach to the game may be implemented. Examples of this include a time limit for planning management actions each turn and designating responsibilities for the gameplay amongst the group, such as one player handling the Aquabucks while another moves the pollution pieces each turn.

Flipping Lakes as a sandbox model

Future applications of Flipping Lakes have the potential to explore new avenues of the game as a scientific sandbox/toy box. Flipping Lakes is specifically suitable as a model for scientific experimentation as there is a full knowledge of pollution sources, lake pollution threshold values and management effectiveness within the game-world. Such a situation is seldom encountered in real-world cases on a catchment-scale (see e.g. van Gils et al. 2019). Therefore, the game may serve as a fictitious arena to experiment with scientific questions revolving around water quality management and decision-making (e.g. a form of a social ecological model, (Mooij et al. 2019)), such as single player versus group decision-making or human versus artificial intelligence in finding optimal solutions to winning the game. Along with these applications, we encourage and support the community (through the open availability of the game) to create new and previously unforeseen uses of Flipping Lakes in communication, education and science.

CONCLUDING REMARKS

Translating water quality issues to a broad audience is necessary to maintain social support for managing the often invisible pollution of our catchments (Dean et al. 2016). Learning and working together to create fictitious solutions, such as with utilizing Flipping Lakes, can stimulate discussions around real-world issues. Importantly, the simplified and structured nature of the game makes participants relay their perspectives and insights in terms of the same tangible system and challenges being presented to everyone (Eisenack 2013). This creates a playing field disconnected (in part) from their real-world stakes (Flood et al. 2018). Being on the same page, or the same board in this case, can translate sectoral terminology into a joint understanding of the water quality issues faced by our lakes.

APPENDIX 1: Flipping Lakes manual

Flipping Lakes

Rules of the game

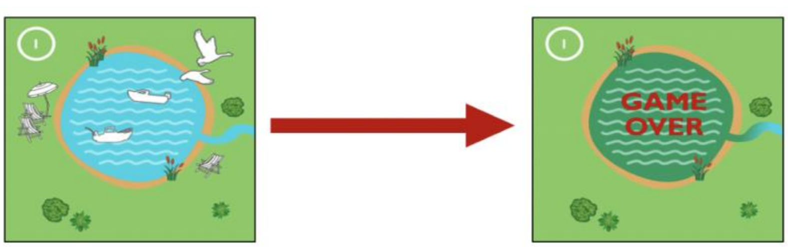
Setting up: Take all catchment cards and design your playing field (the catchment). All special catchment cards (Start card, recreational lake, lakes, pollution sources) need to be connected using connection cards (rivers and streams).

Goal of the game: You are a water manager tasked with keeping pollution out of a recreational lake that is located at the end of your catchment. If pollution does reach the lake, it will become a blue-green algal dominated mess and you lose the game! Managing your catchment effectively will help to stop the pollution. Watch out for societal and climatic events that may occur as they may change the game as you go. When other lakes within the catchment become too polluted they will flip, turning them into turbid systems and ultimately adding to the pollution of the catchment. Keeping your lakes clean and clear will help you to achieve your goals. Will you manage to keep your recreation area up and running?

Playing the game: The player is challenged to manage the system for 15 turns, with each turn representing one year of management. During each turn the player will:

1. Flip an event card for the given turn.
2. Receive taxes. Tax income constitutes 3 Aquabucks.
3. Enact measures if money is sufficient and the player wants to.
4. Add pollution from pollution source(s).
5. Remove pollution due to retention or purification (i.e. bank filtration, clear lakes)
6. Move pollution chips. Default pollution flow speed is one catchment card per turn.
7. Count pollution chips on each lake. If the lake is in clear state and the number of chips exceed the pollution threshold value, flip the lake to the turbid side. If the lake is in a turbid state and the number of chips is lower or equal to the pollution threshold value, flip it to the clear side.
8. Check if pollution has reached your focal lake. If so, GAME OVER! If not, begin the next turn (repeat steps a-f).

End of the game: If the pollution has not reached the nature area after 15 years, you have won the game. You get two points + one bonus point for every lake you have managed to keep in a good ecological state.



Measure cards

Predictive model (1 Aquabucks*):* Predict the future climate (social and climatic) and check what the event in the following turn will be.

Increase public awareness (2 Aquabucks): Played directly on an urban card, it reduces pollution loads by 1. Played on a lake it will protect it from the influences of duck feeding and dog poop events.

Bank filtration (3 Aquabucks*):* remove one pollution per turn on the given catchment card (assuming there are any).

Sediment capping (3 Aquabucks*):* Stops pollution load from a lake itself (only useful for turbid lakes).

*Dam (*5 Aquabucks*):* Close off one connection in your catchment. Pollution will not travel beyond this point unless there is an extreme rainfall event.

Increase water storage capacity (6 Aquabucks*):* When used on a sewage overflow this card stops the loading from the overflow. When used on other catchment cards it allows the pollution to be held in place for one extra turn. Place the water storage chip on the catchment card.

Dredging (8 Aquabucks*):* Remove all pollution from one catchment card one single time.

Agricultural legislation (9 Aquabucks*):* Reduce the pollution load from all farms to 1.

Water treatment plant (10 Aquabucks*):* Place on the catchment to filter out 8 pollutants per turn from this location.

Event cards

Climatic events

Extreme rainfall: Pollution travels two catchment cards per turn, also over dams. Also, all sewage overflows produce pollution this turn.

Heatwave: Pollution gets concentrated, multiply all pollution added this turn by 1.5.

Extreme drought: Pollution does not travel this turn, new pollution is added as normal.

Societal events

Dog park: Citizens are requesting a dog park in your catchment. Build one along your catchment by adding the dog chip. The dog chip adds 1 pollution each turn to this catchment card.

Agricultural intensification: Agriculture has intensified in the catchment, each farm in your catchment now produces 1 extra pollution per turn.

Feeding ducks: People have been feeding the ducks in one of your lakes. The excess nutrients have caused the lake to flip. Flip one of your lakes to the turbid state unless a) all lakes are already in the turbid state or b) lakes are protected by *Increase public awareness* on urban catchment cards.

Regular events

Business-as-usual: All normal rules apply.

APPENDIX 2: Lake Science Concepts

Table A2.1.: Lake Science Concepts that were used in the student questionnaire.

	Lake Science Concept	***Concept Description***
General knowledge	*Water quality management*	*Familiarity with the water quality management field*
	Lake water quality and ecology	*Familiarity with lake ecology and water quality processes and terms*
	Watersheds/networks	*Familiarity with area of land where surface water converges and how different water bodies can be connected*
	Extreme climatic events	*Familiarity with extreme events such as drought or flooding caused by changing climates*
	Societal pressures on water quality	*Familiarity with the types of and pathways that social pressures affect water quality*
Local and regional water quality	*Pollution impacts*	*Knowledge of the ways that pollution impacts the lake state and functions*
	Alternative stable states	*Knowledge on the theory of alternative stable states*
	Critical transitions	*Knowledge on the theory of critical lake state transitions*
	Hysteresis	*Knowledge on the application of hysteresis in lake state transitions*
	Internal nutrient loading	*Knowledge of internal nutrient loading processes*
	External pollution loading	*Knowledge of external pollution loading sources and pathways*

	Flow of water and substances	*Knowledge of water movement through a catchment and mobilization of substances*
	Spatial cascading effects in hydrological networks	*Knowledge of influences one water body can have on a connected water body*
Extreme events and management	*Extreme precipitation*	*Knowledge about the occurrence and impacts of extreme precipitation on lakes*
	Extreme heat waves	*Knowledge about the occurrence and impacts of extreme heat waves on lakes*
	Extreme droughts	*Knowledge about the occurrence and impacts of extreme drought events on lakes*
	Proactive measures (mitigation)	*Knowledge on the types and application of management measures that can be taken to proactively mitigate pressures*
	Reactive measures (adaptation)	*Knowledge on types and application of management measures that can retroactively adapt a system to a pressure*
	Long term planning	*Familiarity with methods for forming long-term management plans*
	Short term planning	*Familiarity with methods for forming short-term management plans*

APPENDIX 3: Student consent form

Flipping Lakes Participation Information and Form

This survey presents background information and consent terms for the Flipping Lakes game.

Please read through page 2 with information on participation and page 3 with the terms of agreement. After reading, we ask that you fill-in the three questions on page 3 asking for your name, the date, and your consent for participating in the project. (Also, if you would like to receive updates about the project, you can provide your email address in question four.)

Please click on "Next" to move to page 2. Thanks!

Flipping Lakes Participation Information and Form

The page contains information about participating in the project. After reading through the text, click "Next" to move to the consent form.

Informational letter for participants in the "Flipping Lakes" serious game research project

Thank you for your interest in the serious game "Flipping Lakes." Your involvement with the trial runs of this new communication tool will assist with identifying optimal gameplay approaches, ultimately supporting the game's applications and impact.

At the Netherlands Institute of Ecology ("NIOO"), we employ steps to ensure the professional handling of all data that result from studies with the public. We are therefore providing this informational letter detailing the purpose of this study, the method for gathering data, the use(s) of gathered data and the process of data storage. A consent form outlining your agreement to partake in the study according to these research guidelines is provided at the end of this letter. Contact information for the lead researcher and the NIOO Data Protection and Privacy Officer are also provided at the end of this letter.

Aim of the study

"Flipping Lakes" is a serious game developed within the NIOO Department of Aquatic Ecology to exemplify aquatic environmental challenges that our researchers are studying and on the management challenges that contemporary and future pressures will exacerbate. This game offers a clear and tangible visualization of a large-scale system that players can interact with. The intended aim of both creating and refining this game is to:

- support educational experiences through players learning and managing the ecological and managerial concepts embedded in the game, and
- offer a visualization of scenario-based management to stimulate conversations amongst catchment managers, stakeholders and interested citizens.

How does my participation support this research project?

As this game is intended to be universally applicable and effective, we would like to gather input from individuals from various backgrounds. This includes, but is not limited to, demographics, educational background and expertise.

Voluntary participation

Participation in this study is voluntary. If you do participate but wish to withdraw at a later stage, your data will be removed from the study. Your withdrawal can occur at any point during or after the study, but your data may be included in the research article if the request occurs after the article is submitted and/or published in a peer-reviewed journal.

What happens if I participate?

We are gathering input about the usability, applicability and effectivity of the Flipping Lakes game through demonstrations and pre-designed gameplay. Your participation in the study provides feedback on your experience. The gathered data will be used to improve the game and/or promote the game as an effective tool for other researchers, water managers and educational instructors to use. There are two ways in which your participation can facilitate these research study aims. First, demonstration games will be led by members of the creative team. Your involvement with playing the game and offering verbal or written feedback will be noted as evidence of the game's real-world applicability. Second, a series of pre-designed gameplay is testing the impact of different scenarios on individual learning. Your participation in the form of either self-scoring your familiarity with ecological and managerial concepts before and after gameplay and/or recording actions taken during each round of the gameplay will proffer data for statistical analysis of the game's impact.

Advantages and disadvantages of participation

There are no foreseen disadvantages to participating in this study. Any results arising from the trial runs of the game (demonstration games and pre-designed gameplay situations) will be used in refining the game and communicating this tool for other professional and interested persons to utilize. T

To what extent is my participation confidential?
The NIOO practices an Open Access policy in which all published data will be accessible to the public. All sensitive data gathered during research will be protected through anonymization of personal information, such as name, employment position and contact information.

We are obliged to archive your research data. Participation in this study implies permission to do so. With this, we follow the relevant regulations, such as the EU General Data Protection Regulation (GDPR) and the NIOO's best management practice guidelines. During the research project, your data are only accessible to researchers from the NIOO that are working on the project. You can always contact the researchers if you wish to have access to your data.

Written and verbal communications about these game data (as outlined in the following section) will preserve the confidentiality of participants.

What happens with the results of this study?
Data will be used to demonstrate the applications of Flipping Lakes within professional, educational and other contexts. The results of this study will therefore be used as examples of the game's implementation. Your responses (verbal or written feedback, self-scoring data and game record) will be summarized in a scientific article that will be published in a peer-reviewed journal. Other communications about the Flipping Lakes game, such as on the online webpage, during verbal discussions, in presentations and in other scientific publications, can also include the anonymized results when discussing outcomes of the game's application.

As stated previously, you may withdraw from the research project at any point, but your data may be included in the scientific article if your withdrawal request occurs after the article has been submitted and/or published in a peer-reviewed journal.

Who should I contact if I want more details on this study?
If you have any questions or want more information, you can contact Maggie Armstrong (see below for contact details) or the researcher with whom you've been in contact. If you wish to learn more on the data management policy of the NIOO, you can contact the Data Protection Officer at P.vandenBerg@nioo.knaw.nl and the Privacy Coordinator at s.bekker@nioo.knaw.nl.

Thank you for reading this informational letter and for your careful consideration whether to participate in this study. If you agree with the above guidelines, we will ask you to sign and date the consent form below.

Maggie Armstrong
MANTEL@nioo.knaw.nl
Netherlands Institute of Ecology
Droevendaalsesteeg 10
6708 PB Wageningen
https://nioo.knaw.nl/en
+31 (0)317-473400

Flipping Lakes Participation Information and Form

The page contains the Consent Form with the Terms of Agreement. Please read through the text and respond to the four questions. Once you have finished, please click "Done" to submit the survey.

Consent form

At the Netherlands Institute of Ecology ("NIOO"), we employ steps to ensure the professional handling of all data that result from studies with the public. In combination with the informational letter detailing the purpose and guidelines of this research project, there is also a consent form. We kindly ask that you complete the following form to confirm your acknowledgement of the research guidelines and your agreement to participate in the study.

Project

Applications and testing of the serious game "Flipping Lakes"

Terms of Agreement

Declaration of the respondent:

By consenting the participating in this study, I acknowledge the following statements to be true:

> I have received the information on the goals of the study on "Flipping Lakes," and I have read and understood this information.

>I have had sufficient time to consider my participation. I have been able to ask questions. These questions have been satisfactorily answered.

>I grant permission for participation in this study.

>I know participation in this study is voluntary, and that I can withdraw my permission during the research without having to motivate that choice.

>I assent to using my research data as described in the information letter under the header 'To what extent is my participation confidential'?

>I understand that the information obtained from this research will be saved in a protected environment.

* 1. Your name:

* 2. Today's date:

* 3. I have read the provided research project information and the Terms of Agreement. I acknowledge and consent to the terms for participating in this study.

◯ Yes, this statement is correct.

4. Would you like to receive notifications or a weblink to the publication(s) that result from this project?

◯ Yes, I would like to be notified of the publication(s) that result from this work

◯ Yes, I would like to receive a website link to the peer-reviewed publication

If you would like to receive information, please give your email address here:

APPENDIX 4: Perceived learning by concept

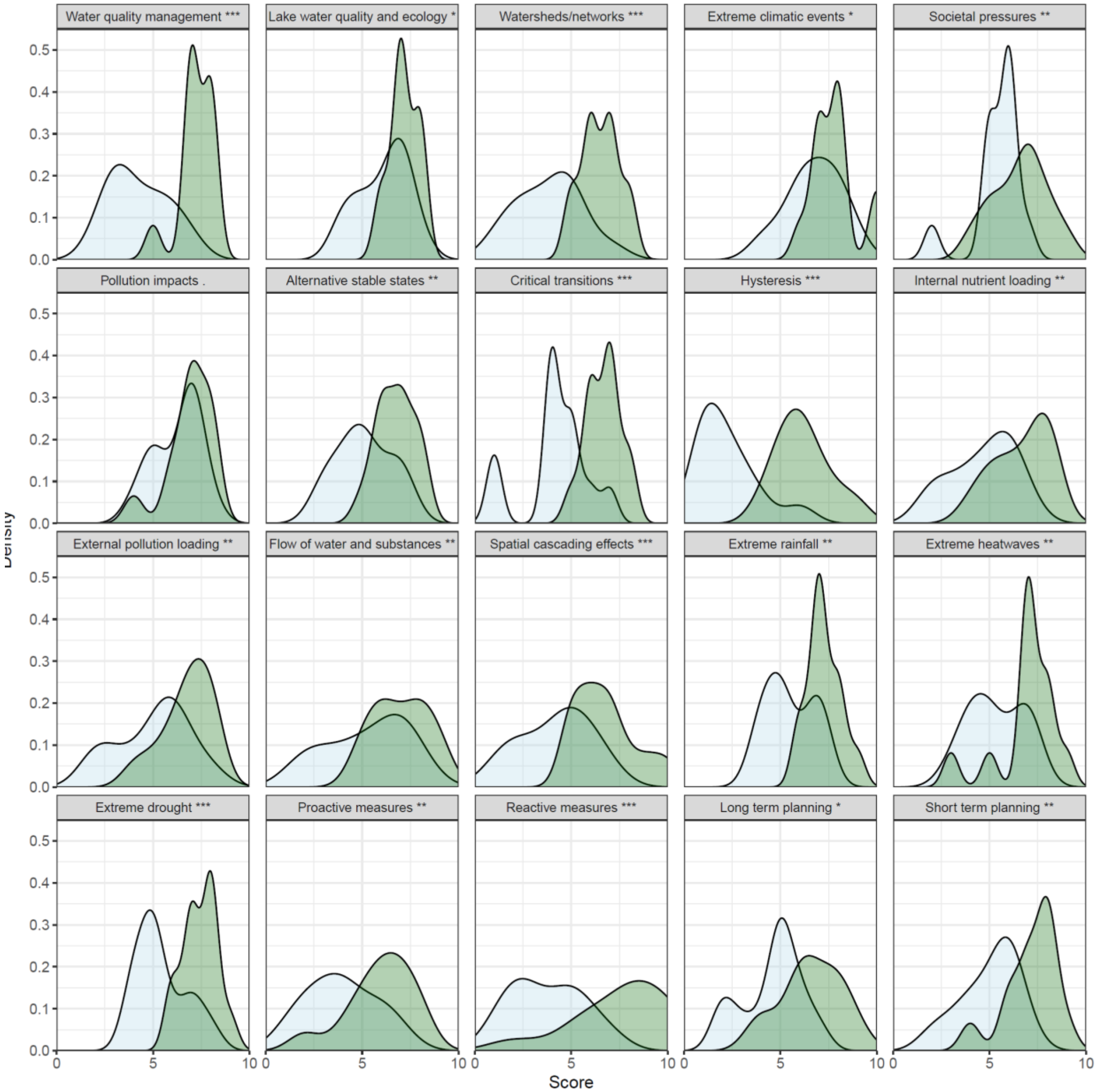


Figure A4.1.: The level of perceived concept knowledge by university students (n=12) before playing Flipping Lakes (light blue) and after (dark green) for different concepts contained within the game. The scores (x-axis) range between 0 (not familiar with the concept) to 10 (expert on the concept). The results of the students' scores were analyzed using a paired Two-sample Fisher-Pitman permutation test. Symbols indicate significance with ***: P<0.001, **: P<0.01, *: P<0.05, ·: P<0.1).

Chapter Four -
Opportunities for improving the role of science in lake management: Lessons from North America and Europe

Armstrong, M., Kramer, L., Acuña, V., Antão-Geraldes, A.M., Borre, L., Dieperink, C., Ibelings, B.W., Rusak, J.A., Stelzer, J.A.A., Teurlincx, S., Yokota, K., and de Senerpont Domis, L.N. (2023) Opportunities for improving the role of science in lake management: Lessons from North America and Europe. Manuscript under editing.

1. Overview

1.1 Freshwater lakes' services and challenges

Freshwater lakes provide a range of provisioning, regulating, supporting and cultural services (Haines-Young and Potschin, 2011). This diversity of services offers the opportunity for disparate societal sectors to receive abundant benefits. However, there are limitations on the capability of lakes to provide services. In conjunction with the increasing human demands (e.g water abstractions), water systems are experiencing multiple, coinciding pressures often related to anthropogenic activities (e.g. land use change, altered flow regimes, climate forcing; Falkenmark et al., 2019). The cumulation of pressures within the catchment can affect the functioning of lakes, in turn influencing the capacity for these socio-economic systems (defined as "systems that may have social and/or economic implications as a result of pressures, system shifts, function changes," e.g. Heggerud et al., 2021) to provide services. Ergo, alterations within the catchment can impose pressures on lake systems, such as when urbanization and agricultural intensification alter the quality, quantity and temporal distribution of water (Heino et al., 2021). This is evident with the ongoing freshwater biodiversity crisis (Albert et al., 2021) and the prominence of lake eutrophication triggering harmful cyanobacterial blooms (e.g. Stoddard et al., 2016), which can affect the provisioning of lake functions and services (Huisman et al., 2018).

Managing multiple pressures for continued lake functionality and services will require intersectoral efforts that enable adaptive lake management. Enhancing the incorporation of scientific knowledge in water management discussions is critical for developing informed action plans targeted at these pressures. While successful intersectoral partnerships have been observed (e.g. Bartram et al., 2002; Huot et al., 2019), there is still room for further insights, development and improvement at the lake science-management intersect (Josefsson & Baaner, 2011; Voulvoulis et al., 2017). Here, we aimed at a better understanding on the extent that science is currently incorporated into lake management across continents and to identify opportunities for improving or extending the role of science in lake management. As local-level lake management goals may differ between regions due to national or international policies driving the legislation requirements, there can be regionally different roles or applications of science that inform decision-making.

1.2 Integration of science in lake management

While there have been tremendous efforts towards improving the scientific underpinning of policy and management (Coleman et al., 2017), the fast pace of environmental change leaves ample room for exploring different avenues to increase the uptake of science in day-to-day management (Rogers, 1998). Uncertainties in decision-making can arise from a number of sources including the multitude of anthropogenic, climatic and intrinsic pressures; their potential synergistic effects; and the demands of stakeholders and other users amongst other pressing issues (Quinn et al., 2017). Context-dependent uncertainty can also create situations in which typical management practices alone are not equipped to resolve the pressure (Peterson et al., 2003). Rather, practices such as adaptive management can support the combined knowledge of management and science to optimize interventions in lake conservation (Abdel-Fattah & Krantzberg, 2014; Yasarer & Sturm, 2016). Practical implementation of these combined approaches have been observed around the globe (Brown et al., 2011; Li et al., 2020; Olsson & Folke, 2001), but there is still room for growth and identification of new approaches to sustainable intersectoral partnerships (McLain & Lee, 1996). Overall, more decisive actions towards increasing the degree of integration of lake science and management sectors into more cohesive collaborations are needed to address lake challenges (Creed et al., 2016; Roux et al., 2006). Optimal intersectoral partnerships can foster more effective management outcomes in cases of joint knowledge production (Hegger & Dieperink, 2014) and decision-making under uncertainties (Stoffels et al., 2021; Yokomizo et al., 2014).

Disconnects between science and management sectors can affect the development and efficacy of cross-sectoral collaborations (Dreelin & Rose, 2008). Various reasons have been cited as the impetus behind such disconnects. For instance, the significance and applicability of scientific insights can be undermined when other sectors perceive the role of science as merely for increasing economic growth or for advancing innovation (Hallonsten, 2021). Other barriers to intersectoral knowledge sharing include inherent cultural differences, obstacles within institutional bureaucracy, scientific knowledge not being appropriately accessible and a misalignment of the research outcomes with management needs (Cvitanovic et al., 2016). Disconnects can occur during any point of developing and sharing scientific knowledge. At the beginning of scientific studies, lack of guidance on how to establish and develop research plans that highlight knowledge exchange may be a barrier (Cvitanovic et al., 2016). Following study completion, the failure to translate scientific knowledge into management and policy arenas diminishes the ability for scientists to assist in supporting decision-making processes (Laurent et al., 2015). For example, the provisioning of data is ineffective when the metadata (supporting information on the data) is not provided or translated for management purposes (Laurent et al., 2015). Additionally, a lack of targeted dissemination can cause decision-makers to be unaware of the insights and tools, resulting in their exclusion from management discussions and planning (Cvitanovic et al., 2016). The direct integration of scientists onto decision-making boards can ensure that there is scientific representation in the discussions, but this is only effective if the discussion content is accessible to other board members and jargon is avoided (Laurent et al., 2015).

1.3 Regional differences in water legislation

Improved health and functioning of lake ecosystems are common goals of lake management, although the methods to achieve these goals can differ across geographic regions. Specifically, legislative requirements could affect the methods being applied to manage ecosystem functioning and uses (Ebbesson, 2010). On a regional scale, the comparison of laws in North America and Europe shows a fundamental difference in the approaches being taken.

In North America, the United States Clean Water Act (“USCWA”; 1972) aims to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters." The USCWA hinges on the water management of navigable waters through the establishment of water quality standards. Water bodies that fail to meet the set water quality standards are required to develop a total maximum daily load (“TMDL”) for each pollutant (e.g. Fakhraei et al., 2014). While historically the challenges that have affected water quality were point source pollutants from discernible outlets, such as heavy metals and polychlorinated biphenyls from industrial pipelines, the more problematic sources today are non-point (“diffuse") source pollutants (Andreen & Filler, 2004). Ideally, the TMDLs are based on the latest science and are tailored to maintain the designated use of the water body (e.g. public water source, industrial water source, species habitat; Duggan & Kotalik, 2020). Given the significant complexity of managing diffuse pollutants, the shift into a more holistic management approach to reduce pollutants will be key (Boyd, 2000).

Similarly, Canada has legislation that is aimed at the quality of its nations waters. The Canada Water Act ("CWA"; 1985), for instance, is an overarching national legislation supporting frameworks for conserving, developing and using the available water resources for the interest of all Canadians. The main aim of the CWA is to foster across federal-state collaboration. Indicators of freshwater quality for the CWA have been developed based on a surface water system's capacity to support aquatic life (Canada & Environment and Climate Change Canada, 2021). Overall surface water quality is calculated and categorized according to whether the water quality guidelines have been met (scope), how often the guideline has been met (frequency) and how large the deviation was when the guideline was not met (magnitude; Rosemond et al., 2009). Unfortunately, these guidelines are not enforced (Van Winckel et al., 2021), leaving ample room for interpretation and implementation of water quality management. Specific pollution regulations are instead administered through federal laws such as the Canadian Environmental Protection Act, the Fisheries Act and the Canadian Environmental Assessment Act which have a strong focus on (and identification of) point source pollutants.

In Europe, the Water Framework Directive ("WFD"; WFD/2000/60/EC; 2000) for all European Member States aims at emphasizing environmental sustainability in order to ensure that all surface waters achieve good ecological status by 2027 (Voulvoulis et al., 2017). The WFD intended to replace the old water management paradigm of controlling pressures in isolation through a new approach of holistic and integrated considerations, developing river basin plans and using more realistic delineations of management areas. In comparison to North America's focus on point source pollution, the WFD mandates that all waters achieve good ecological status based on a broader assessment of environmental health. Within the WFD, science is also called upon to stimulate the development of comparable ecosystem state reference conditions and other metrics (Reyjol et al., 2014). All included water bodies must acquire the outlined reference status including physical, chemical and biological parameters. Upon failing to meet the "good" level for one or more parameters water bodies are disqualified from achieving the mandated "good" ecological status, making the utilization of best available knowledge for informing management important. Unfortunately, there are still challenges in integrating science and management knowledge to accomplish the WFD goal, such as the coordination of research to meet the timing of and applicability for management needs (Quevauviller et al., 2005).

Concerted efforts to develop the science-policy interface has been leading national and international governing bodies to establish guiding visions of water ecosystems that strike a sustainable balance between conservation and utilization (Unesco, 2015), such as those described above. Utilizing science to assess this fine distinction between too much or too little of either mindset can help move societies into an era of conscientious stewardship of systems (e.g. Bridgewater, 2021). Implementing this balance at the management level, however, can be challenging as the day-to-day maintenance of the system can be convoluted by having to meet policy targets and goals; mitigating multiple, coinciding pressures; accounting for numerous and, occasionally, conflicting ecosystem uses; incorporating competing stakeholder demands; and doing so under limited budgetary and jurisdiction constraints. Despite science being involved in guiding policy, science is still needed at the management level to inform planning and actions (Roux et al., 2006). Using scientific insights to help make actionable local-level plans based on the national policies can ease the translation of the broad legislation goals.

1.4 Scope of the paper

Our study is rooted in an expressed desire of lake scientists (defined as individuals focused on the research of and knowledge-development regarding lake systems) to become more effective collaborative partners for lake managers (defined as individuals tasked with decision-making for developing or implementing management actions for a lake system). Numerous frameworks, such as the adaptive co-management approach (Armitage et al., 2009), similarly advocate for the further integration of science and management. However, it can be challenging to bridge sectoral understanding of what tasks scientists can undertake to assist lake managers and what communication methods should be employed. This paper aims to address these challenges by ascertaining the existing and potential roles of science in lake management and by identifying opportunities for increased collaborations, sharing of knowledge (e.g. Wen et al., 2015) and developing more intersectoral-based plans (Lin et al., 2013).

As the lake pressures, uses and policy requirements can manifest differently according to regional situations, there can be differences in the environmental challenges that managers could be handling. We therefore expected that these challenges hindering lake management, as indicated by managers, would vary between the study regions as pressures are likely different across continents. Given the difference in legislation across the continents, we also hypothesized that managers would identify region-specific opportunities to expand the role of science throughout management structures.

2. Methods

We gathered lake manager perspectives through two mediums, i.e. online surveys and qualitative interviews. Lake managers globally were encouraged to participate by providing their perspective on management challenges and collaboration opportunities. Qualitative interviews were also conducted with lake managers and collaborators that work with the European Union's Water Framework Directive.

2.1 Online survey

We developed an online survey to garner an overview of perspectives from lake management-oriented individuals regarding science applications within lake management and how scientists can be effective collaborators (see Appendix 1 for full survey). In recognition that the delineation of "manager" and "scientist" can be confounded by overlapping tasks and responsibilities, respondents could identify themselves as a lake manager, a scientist, both or other. The classification of their role in lake management and the primary country their work is conducted in were gathered to establish demographic information (questions 2-6).

The survey queried four lines of questioning all aimed at attaining a deeper understanding of lake manager perspectives and identifying methods for improving intersectoral collaborations. The first theme focused on the challenges affecting lake management (including pressures that are affecting the system), the uses of the system by stakeholders (defined as individuals or groups that utilize the services of the lake) and the requirements that are set by legislation (questions 7-9).

The second related to the application of scientific information in management decision-making (questions 10-12). Managers were asked to explain how scientific information is currently being utilized within their management process ("realised") versus when managers believe scientific information should be applied ("potential"). Additionally, the sources when managers gather scientific information were identified.

The third theme related to the role that scientists fill in management decision-making (questions 16-21). These questions were aimed at when scientists were involved in the lake management discussions that were held within management organizations ("management discussions") and that were conducted with outside stakeholder groups ("stakeholder discussions"). For both types of discussions, managers relayed when scientists have participated in the discussions ("realised") versus when managers believe that scientists should be involved ("potential").

The final theme related to methods for improving knowledge-sharing and communication across sectors (questions 14-15, 22-23). The queried concepts included what managers' preferred communication methods are, how to improve scientific information accessibility and what communication and collaboration challenges are present in intersectoral partnerships. Having an overview of these questions can assist in optimizing the dissemination of sectoral knowledge.

The survey was reviewed by representatives of our target audience to assess user-friendliness and question content. Multiple lake manager beta testers assisted in refining the survey for optimal accessibility during two trials. The first trial was held with lake management professionals from the Muskoka region of Ontario, Canada. A second set of lake manager beta testers was gathered from the North American Lake Management Society.

Two complementary sampling regimes were applied to ensure the survey was received by a representative group of respondents. First, the surveys were disseminated according to a stratified design. To this end, we distributed electronic invitations for participation to a selection of water managers using continents as strata (i.e.North America, Europe) in order to promote a diversity of responses according to regional location. Recipients were encouraged to share the invitation with other water managers that may have been interested in participating in the study. Second, we applied snowball convenience sampling (Seelen et al., 2019) by advertising the survey on social media platforms (e.g. Twitter Inc., LinkedIn®, Facebook Inc.) as a method to improve visibility and to engage a wider range of recipients beyond the aforementioned regions of interest.

The survey was accessible online through the platform Surveymonkey®. The survey link was active from June to October 2020. All responses were collected and stored by the Netherlands Institute of Ecology (NIOO-KNAW) according to the European Union's General Data Protection Regulation (GDPR) and the NIOO-KNAW data policy regarding data archiving with FAIR principles (nioo.knaw.nl/en/fair-data-ecology-and-evolution). Both the survey and data management plan were also reviewed by an internal ethics committee. Respondents were informed about the study participation details and asked for explicit consent within the electronic survey form (Appendix 1).

Survey responses were quality controlled by removing incomplete responses from the database. Removed responses included 1) surveys where respondents did not consent to the participation terms (automatic disqualification in the survey), 2) surveys where less than 60% of the questions were answered (as a threshold for ensuring the majority of questions had a response) and 3) surveys where the country of operation was not specified. The survey yielded 68 complete responses. To allow for regional comparisons, the responses were grouped with the United States of America and Canada combined into North America and Europe as the European Union (Appendix 2). Weighing the corresponding number of responses within the regional categorization supported the direct comparison of manager perspectives between the North American and the European groups. Assessment of the responses from single choice, multiple choice and open-ended questions was conducted through descriptive analysis and using *ggplot2* (Villanueva & Chen, 2019).

2.2 Qualitative interviews

European manager survey responses were supplemented with information gathered during interviews conducted with lake managers on the influence of the Water Framework Directive on ecosystem management. Semi-structured interviews (defined as "interviews with predetermined, open-ended questions that respondents have flexibility in answering," (McIntosh & Morse, 2015) were conducted based on a set of questions on the WFD and the management organization's duties. Managers were asked to elaborate on their process of and challenges hindering achieving the legislation-mandated goals within their management purview. The interview questions related to 1) the challenges affecting the water systems within the organization's jurisdiction, 2) pressures and state of the water management area both presently and historically, 3) the creation and implementation process for the Programme of Measures and 4) public involvement during the management process. Insights from the interviews have been included to provide additional, relevant information to address the underlying research question on how the collaboration of lake scientists and managers can be improved. The first and second question sets relate to theme one of the survey. The third interview question set is closely related to the involvement of scientific information and scientists in the management process. In particular, managers explained the process of developing the River Basin Management Plans that guide management actions in their jurisdiction, including what source(s) of scientific information are used and what collaborations support their plan implementation. The final interview question set similarly supports understanding of the collaborations that managers undertake and identifies preferred collaboration methods.

Nine interviews were held between September 2018 and May 2019 (Appendix 3). The interviews were either conducted in-person or through teleconference and lasted between one to two and a half hours. The interviewed water managers were associated with seven designated water authority organizations (five from the Netherlands, one from Spain, one from the United Kingdom) and two collaborator organizations (one from Spain, one from the United Kingdom). Recordings were taken from all of the interviews with consent of the interviewed party in order to conduct a thematic content analysis on the qualitative responses.

3. Results

3.1 Online survey

Manager responses from the North America (n=47, "NA") and Europe (n=15, "EU") regional groups were compared for similarities and differences. Each completed survey was representative of the respondent's organization, exemplifying each group's approach to and perspective on intersectoral collaborations with scientists. All of the survey data have been expressed as percentages to illustrate how many respondents from the respective regional groups selected the survey answer option.

3.1.1 Management challenges and goals

Respondents were asked to indicate the primary management goals that the organizations strive for, the significant pressures that are affecting lake ecosystems and the uses of the lake system. The most highly-ranked management goals of the respondents' organization (Figure 1a, more than 50%) for North America were water quality (91%), recreation (66%) and biodiversity conservation (57%). European respondents identified biodiversity conservation (80%) and water quality (67%) as the most significant management goals.

Respondents indicated their most significant management challenges based on the 15 listed pressures. The North American group responded that habitat degradation (72%) and invasive species (72%) were prevalent problems. European responses indicated habitat degradation (73%), eutrophication (73%), biodiversity loss (60%) and invasive species (60%) as pressing challenges (Figure 1a).

Lake ecosystem services used by citizens, stakeholders and visitors were selected from a list containing 22 services from all four of the ecosystem service types (Figure 1b). The five most common services in North America were in-water recreation (e.g. swimming; cultural service; 94%), shoreline recreation (e.g. fishing from the shore; cultural service; 91%), aesthetic values (cultural service; 85%), species habitat (supporting service; 81%) and the tourism industry (cultural service; 70%). The most common lake use according to the European respondents was tied between in-water recreation (cultural service; 73%), aesthetic values (cultural service; 73%), research (cultural service; 73%), drinking water source (provisioning service; 73%) and biodiversity (e.g. genetic material; cultural service; 73%). The second most common use was also tied between the tourism industry (cultural service; 67%) and cultural heritage values (cultural service; 67%).

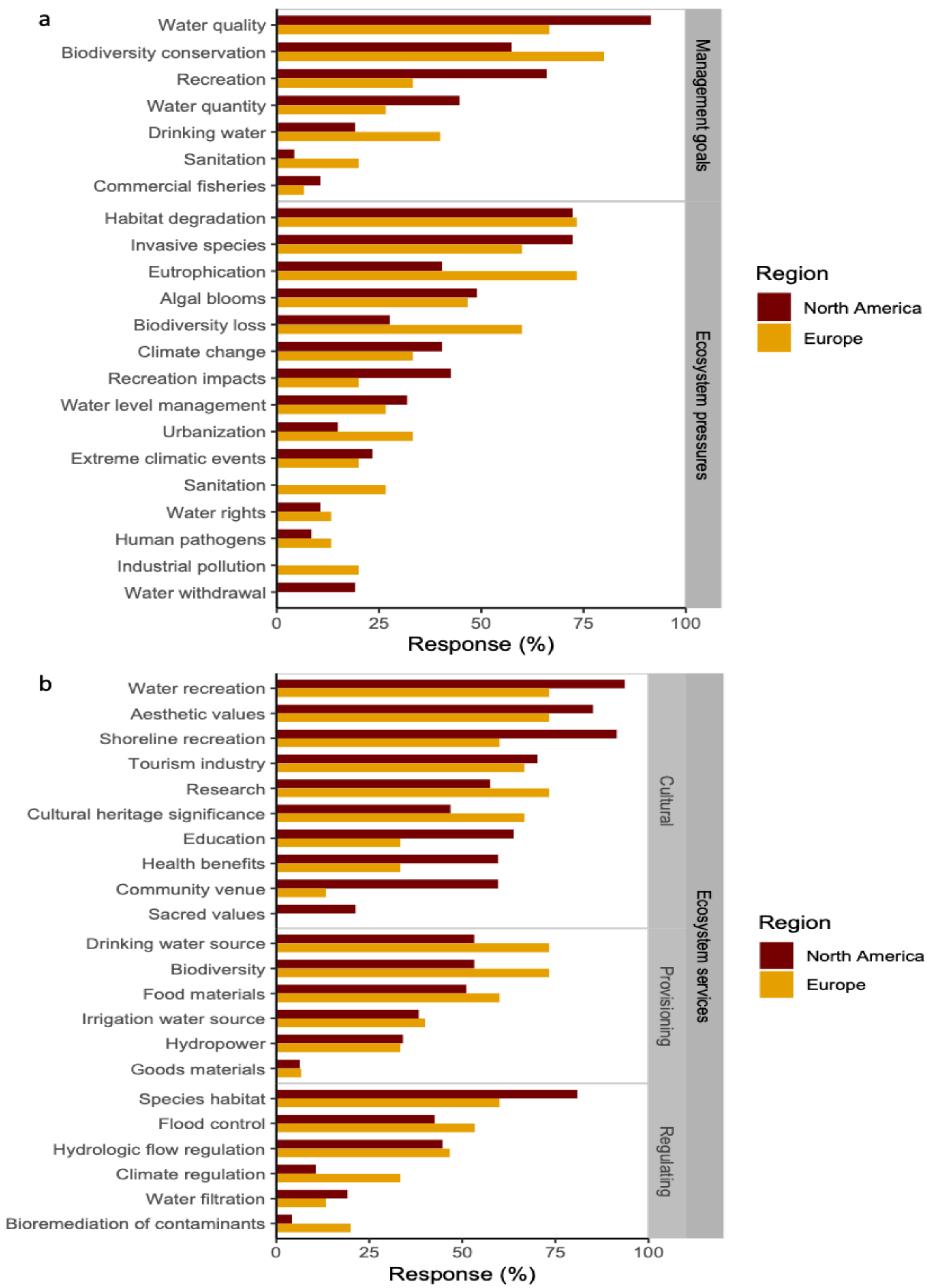


Figure 1: Regional comparison of the management constraints (i.e. management goals and ecosystem pressures; 1a) and the ecosystem services (1b) incorporated in lake management, by percent of regional manager responses (North America n=47, Europe n=15).

3.1.2 Applications of scientific output in management

We assessed the role of scientific information in management according to its application throughout management processes. Respondents were first asked about how scientific information is currently realised in their management processes (Figure 2). Among the North American and European respondent groups, the current applications of science in management include improving methods and tools for lake remediation and monitoring (70% NA, 73% EU), providing models and projections of future challenges (55% NA, 60% EU) and offering holistic insight into the wider impacts of management actions on the lake system (51% NA, 60% EU). The two regions differ with NA respondents also reporting applications of suggesting approaches for methods and tools to be used (79% NA) and assessing the effectiveness of actions in meeting the management goal (85% NA) whereas EU managers also indicated that reviewing pollution thresholds (67%) was important.

Respondents were then asked which aspects of the management process scientific information should be included in, i.e. what would be the potential for expanding knowledge applications (Figure 2). According to respondents from both regions, scientific information should be applied in all listed aspects of the decision-making process (over 50% of respondents). The percentage of responses for each answer option increased between the realised and potential applications of scientific information, indicating a perceived opportunity for its further involvement in management processes. Only for "improving methods" and "reviewing pollution thresholds" did the percentage of European respondents decrease between the realised to potential questions, denoting that while scientific information should be incorporated in these tasks, there is no perceived room for further involvement.

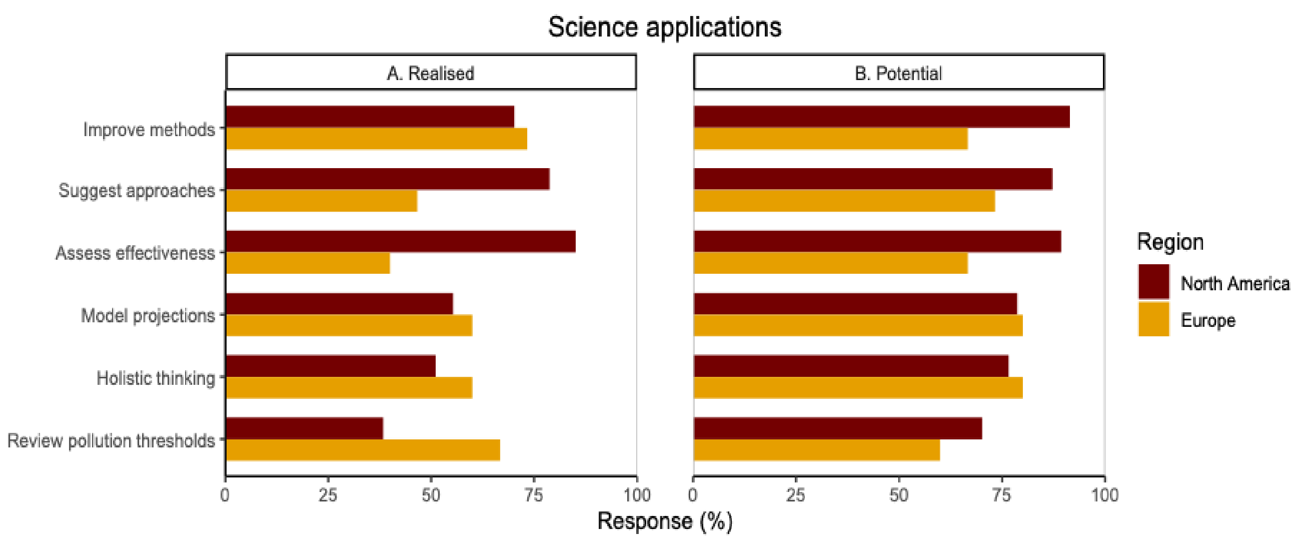


Figure 2: Regional comparison of the realised versus potential applications of scientific information in lake management, by percent of regional manager responses (North America n=47, Europe n=15).

When inquiring after the sources of the scientific information that are used, survey respondents identified nearly all of the options as utilized knowledge sources (over 50% of respondents; Figure 3). The exception was the use of citizen science for acquiring scientific data with only 20% of the European respondents having indicated this option as one that their management organization uses.

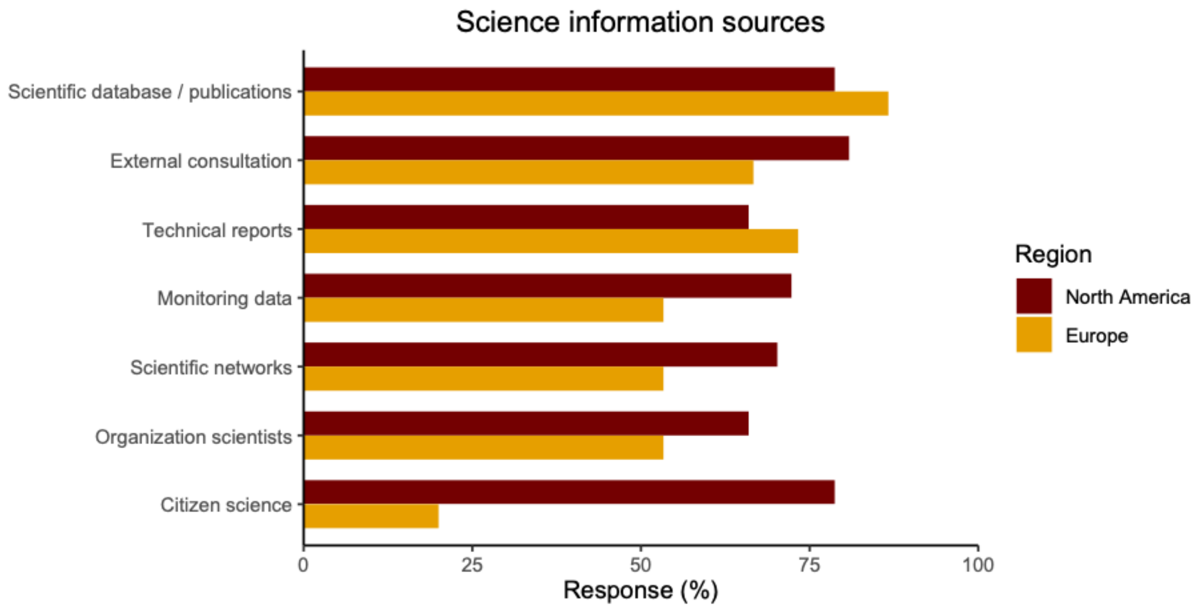


Figure 3: Regional comparison of science information sources utilized by managers, by percent of regional manager responses (North America n=47, Europe n=15).

3.1.3 Role of scientists in management

Lake managers were asked when scientists, both those that are based within their management organization and with outside institutions, are currently involved in management discussions (defined as management-related discussions that are held amongst lake managers of a given organization; Figure 4a) and stakeholder discussions (defined as lake management-related discussions that lake managers conducted with outside stakeholders groups such as fishing organizations and conservation groups; Figure 4b). In North America, survey results indicated that scientists are involved in all steps for both management discussions and for stakeholder discussions (over 50% of respondents). In Europe, lake managers demonstrated that scientists are typically only involved before both types of discussions occur in order to help managers gather knowledge (e.g. attain advice on issues that should be addressed, ideas on how to manage challenges; 47% and 60%, respectively).

Complementary questions were asked regarding when lake managers believe that scientists should be involved in management and stakeholder discussions. In NA, managers responded that scientists should be included in all of the stages (i.e. all answer options) of both discussion types. In comparison, the majority of EU respondents (over 50% of respondents) only identified a potential for intersectoral collaboration in management and stakeholder discussions through scientists helping to gather information before the discussions start (60% and 73%, respectively) and through assessing the impact of management actions (67% and 67%, respectively). A larger number of respondents for potential roles of scientists as opposed to realised roles for nearly all of the answer options for both discussion types, illustrated a perceived opportunity for increased intersectoral collaborations in North America and Europe.

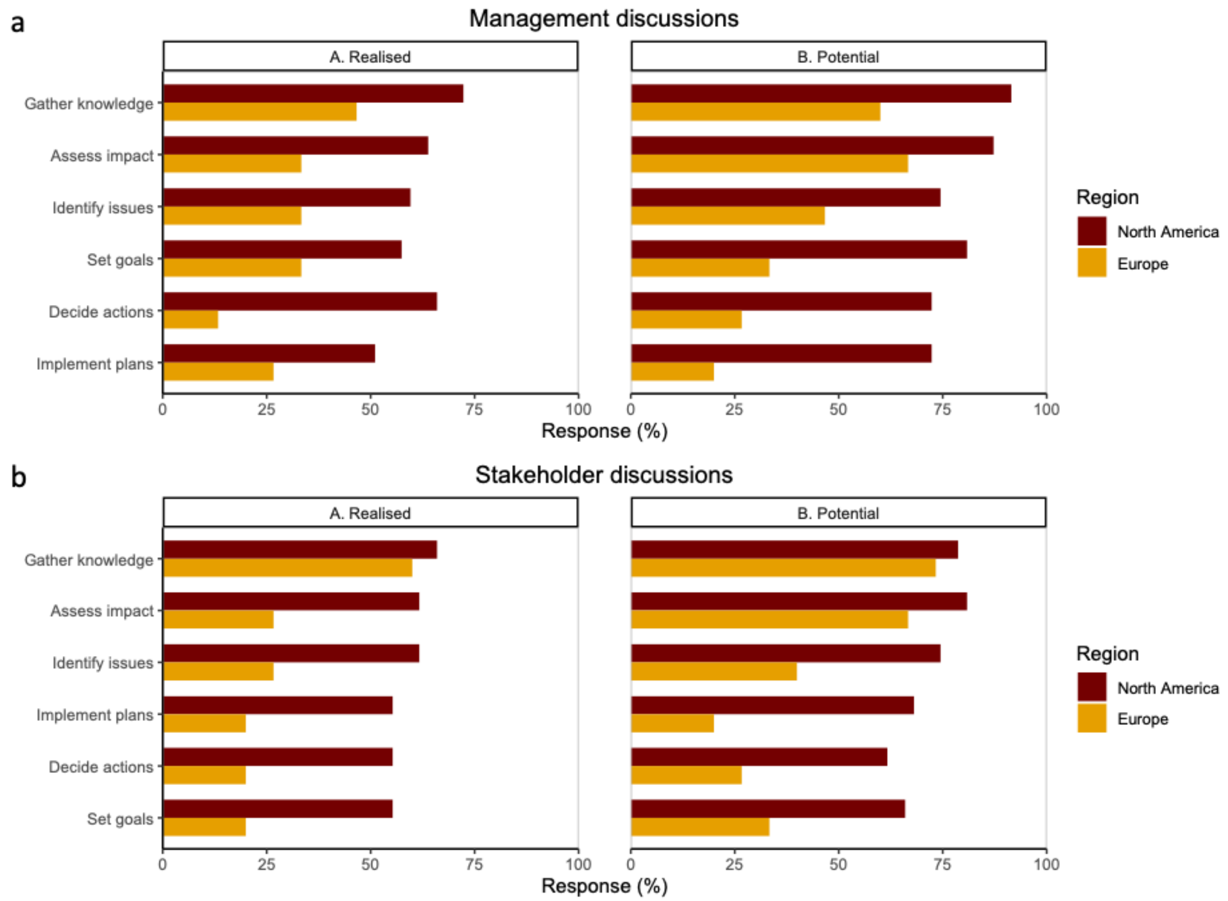


Figure 4: Regional comparison of the realised versus potential roles of scientists in management discussions conducted within the management organization (4a) and with lake stakeholders (4b), by percent of regional manager responses (North America n=47, Europe n=15).

3.1.4 Engagement methods

We assessed communication and collaboration methods through questions on challenges to collaboration, effective communication methods and suggestions for making research more accessible (Figure 5). For both regions, finding funding in support of collaborations has been the most significant problem (70% NA, 73% EU).

A range of effective communication methods (more than 50% of respondents) were indicated across the regions, including using email and messaging (81% NA, 53% EU), meeting at planned events (e.g. conferences; 70% NA), meeting at offices (51% NA, 53% EU) and using phone communication (66% NA). Also highly ranked was the frequency of the communication rather than the method (73% EU), which was the most common communication-related response for European lake managers.

A number of methods were identified as relevant for making research more transferable, including publishing informational materials (e.g. reports, policy briefs and newsletters; 62% NA, 73% EU), co-designing scientific research questions with managers (55% NA, 53% EU) and presenting information verbally and with tools (e.g. presentations, serious games; 53% EU).

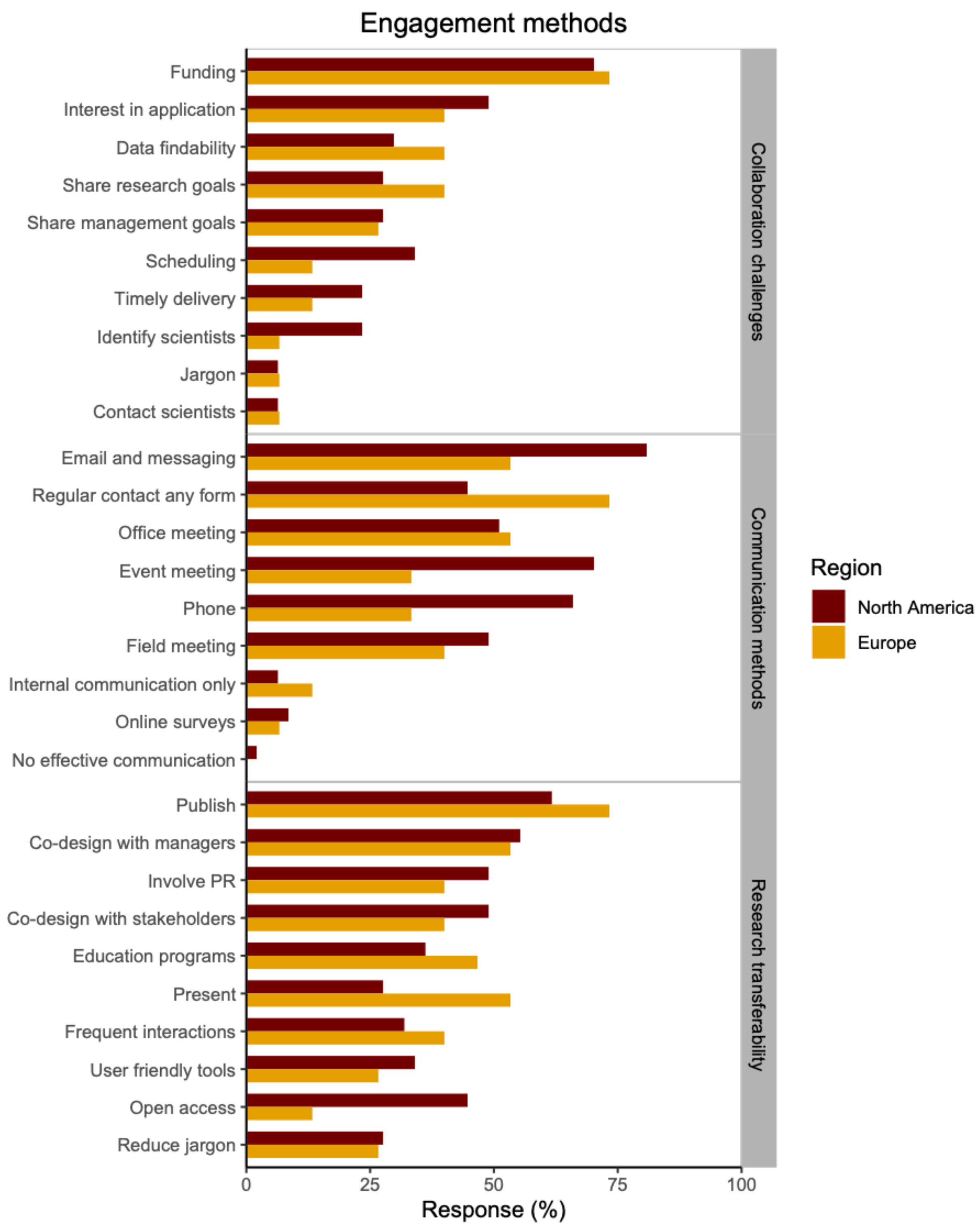


Figure 5: Regional comparison of the challenges affecting intersectoral collaboration, the preferred methods of intersectoral communication and the recommended methods for promoting research transferability, by percent of regional manager responses (North America n=47, Europe n=15).

3.2 Qualitative Interviews

Nine semi-structured interviews were conducted with representatives of organizations throughout Europe. From the responses, it was exemplified that lake management organizations throughout Europe have differing approaches towards implementation of the Water Framework Directive ("WFD"). In part, these deviations in water management were rooted in the challenges and pressures that are impacting lakes within the organization's jurisdiction. For instance, a number of water authorities in the Netherlands and in the United Kingdom commented that water quantity was a large consideration within their decision-making process due to security and flood risk concerns. In comparison, a Spanish authority containing a large metropolitan area cited water quantity and quality as a main concern due to drinking water provisioning that must be provided for the inhabitants.

Commonly expressed during the interviews was the challenge of improving the ecosystem state under the one-out-all-out principle. Advancements in the system state have occurred with various parameters, but the overall status has not changed for a number of authority organizations. As the WFD is moving into the third iterative cycle, many of the short-term and easily implementable measures have already been taken. Additionally, measures which take a longer period to show improvements are underway. For a number of authorities, the current challenge is now reaching the WFD "good" ecological status requirement with more complex or time-consuming measures. The water authorities are also challenged with balancing the "good" ecological status with the disproportionately expensive costs of the remaining measure options. This is compounded with the knowledge that the pressures affecting the water systems, such as nutrient loading and heavy metal contamination, cannot be fully prevented within the catchment.

Five water authorities noted that their Programme of Measures (a set of management actions or interventions that the water authority is responsible for taking) often considered measures that the organization has experience with implementing. However, authorities were also open to new measure ideas, especially if there was scientific evidence supporting the measure effectiveness.

While public involvement is a required component of the WFD, the practical implementation amongst water authorities can differ by the method and degree of engagement. Stakeholders have been engaged in a manner of settings ranging from open town hall discussions to individual stakeholder meetings, such as with agricultural or municipality representatives. These interactions have been noted to occur throughout the planning process, such as during the Programme of Measures development as well as after its completion. The degree of engagement also differed between water authorities. For example, some authorities noted that the implementation of measures was sometimes driven by stakeholder demand, such as with improving the conditions of water systems in the local community. Similarly, stakeholders had been engaged when the measures required hands-on implementation within the community or acquisition of private property. On the other hand, there were instances when the public was less involved in the process, instead being informed about the decisions being made and implemented.

On a similar note, a number of authorities stated that there have been or are ongoing collaborations with scientists that benefited the management goal. For instance, the United Kingdom research organization (which collaborates with the national water authority) has a long history of scientific research conducted within a natural preserve area, supporting decision-making processes for that system under the WFD requirements. Similarly, one water authority expressed a desire for more collaborative opportunities with scientists in order to inform the decision-making process.

4. Discussion

Our study aimed at identifying opportunities to expand the role of scientists as intersectoral collaborators for lake management. Through online surveys and qualitative interviews, lake managers provided perspectives on the challenges affecting lake systems, management goals, the realised and potential role of scientists and scientific information in management as well as suggested knowledge transfer methods. Despite apparent climatic and land use changes between the two continents, the environmental challenges that lake managers perceived were overlapping, reflecting the global environmental crises this planet is facing. In agreement with our expectations, the responses from lake managers suggest regional differences between and within North America and Europe, particularly with regards to the perceived opportunities for growing the collaborative role of scientists in intersectoral partnerships.

4.1 Management challenges and goals

The first theme of our survey illustrated the constraints placed on the management of lake ecosystems through the challenges affecting lake health, the overall goal that managers are tasked with fulfilling and the services being utilized in the systems (Figure 1). Having scientists understanding the pressures and targets that constitute lake managers' goals can assist in framing the parameters of intersectoral collaborations.

The most significant challenges affecting lake systems in both regions were identified as habitat degradation and invasive species, though European managers also reported biodiversity loss and eutrophication as concerns (Figure 1a). These pressures are all tied to the ongoing biodiversity crisis, in which lake ecosystems are particularly susceptible (Dudgeon et al., 2006; Sala et al., 2000). According to the survey, both regions reported water quality and biodiversity conservation as a significant management goal (Figure 1a) which align with the challenges of habitat degradation and invasive species, respectively. Interviewed European managers further identified water quantity, through local scenarios of monitoring water levels or providing sufficient drinking water, as integral to their organization's responsibilities. The links between these management challenges and goals underscores the need to view lake management through a broad scope to understand the complexity and constraints thereof. This is especially true with legislation such as the WFD which mandates strict water quality targets with the one-out-all-out principle.

While lakes are capable of providing multiple services that benefit human communities, stakeholder valuation of the four service types can be skewed (Reynaud & Lanzanova, 2017). Cultural services were indicated by this study's survey respondents to be used more frequently than the other service types (Figure 1b). While knowing why some ecosystem services are more valued than others goes beyond the scope of this study, it may be important for lake managers to have a firm overview of how the lakes are being used as this can influence management actions. For instance, lake managers may be obliged to provide specific ecosystem services that stakeholders demand access to (e.g. Kulczyk et al., 2018). This was witnessed in the WFD interviews as, for example, a Dutch lake was designated for boating uses, therefore requiring that service to be reliably accessible. Similarly, a Spanish water authority was tasked with providing drinking water for a large metropolitan area, making the provisioning of this service a priority in their management planning. Conversely, the uses of the system can instigate pressures which lake managers will then be responsible for mitigating (Grizzetti et al., 2019).

4.2 Scientific knowledge sources and transfer

Theme two assessed the preferred sourcing and applications of scientific information for management processes. Of all the scientific information source options that were provided, scientists have the most agency in their ability to share databases and publish articles (Figure 3). This information source was highly ranked by managers of both regions, which is contrary to the perception of scientists residing in their ivory towers behind publisher paywalls. Managers could default to using journal outlets because scientific outputs tend to be published through this medium. Regardless, knowing this can instill scientists' confidence with the present structuring of scientific academia and its use in science-management collaborations. Transferability of information in journals can always be increased, however (Figure 5). Survey respondents from both regions indicated that co-designing research questions for scientific studies and sharing study findings through other informational materials, such as through publishing policy briefings (e.g. Koontz & Thomas, 2018), can increase the accessibility of the content. Co-creation, public engagement through e.g. citizen science and participatory research agenda setting has been a distinct feature of the EU funding schemes, which could be an impetus for intensifying science-management interactions (Jukić et al., 2019; Robinson et al., 2020).

Managers have demonstrated in previously published literature (e.g. Johns & Teare, 2015) as well as our survey and interviews that there is potential for further applications of scientific knowledge throughout decision-making processes (Figure 2). However, there is a concurrent societal trend of distrust in scientific information (e.g. Fairbrother, 2017; Guidotti, 2017). Instilling or increasing confidence in the validity of scientific insights can help ease both its further applications at the science-management intersection and authority with the public (Pettorelli et al., 2019). Applying "open innovation" in conjunction with an "open access" or "open science" methods can avoid the devaluation of science (Besançon et al., 2020; ElSabry, 2017; Smart et al., 2019). During knowledge production, an established research approach, transparent communication and a transdisciplinary research team can lead to results that are directly and confidently applied to decision-making (e.g. Burkhardt-Holm & Zehnder, 2018; Nguyen et al., 2019). Development of management tools can similarly be accepted when the outcome is both understood by stakeholders and is directly applicable to management or policy (Ulibarri, 2018).

4.3 Role of scientists in management

Theme three focused on the roles of scientists in management discussions taking place within the organization and those held with stakeholders (Figure 4). Regional differences were displayed with North American survey respondents indicating that scientists are currently involved in every step of both types of discussions and that there is potential for further intersectoral involvement. In comparison, European respondents noted that scientists are only currently involved in gathering knowledge before either type of discussion is held and that there was limited opportunity to increase involvement. Additionally, while the degree of involvement varied, interviewed European managers concurred that there have been cases where involvement of stakeholders in the WFD process has been a necessary, and occasionally useful, collaboration.

An explanation for these results could be the basis of the regions' legislation for water management. The European Union Water Framework Directive (WFD) underwent extensive scientific-based vetting at the initiation of the legislation through the intercalibration process and establishment of reference conditions (Poikane et al., 2015). As a result, the parameter targets for management have been well established since the beginning of the Directive's implementation. Scientists could be involved with giving insight on the management actions but, given the WFD's iterative cycle design, these instances would coincide with the six-year cycle for submitting the River Basin Management Plans (e.g. Giakoumis & Voulvoulis, 2018). Scientists are not entirely precluded from collaborating with or supporting the goals of lake managers throughout the WFD cycles, however. There are examples of scientific studies facilitating the evidence-based informing of management through the European Union's HORIZON programme with projects such as MANTEL (https://www.mantel-itn.org/), MARS (http://www.mars-project.eu/) and WISER (http://www.wiser.eu/). The development of tools in these projects was primarily to contribute to more evidence-based decision making.

In comparison, the United States Clean Water Act (USCWA) was formulated for regulating point source pollution and has since shifted more towards diffuse pollution, but a regulatory approach is still applied. Aside from mandated monitoring the water quality of lake systems, scientists can also provide assistance with the development and implementation of the total maximum daily loads (TMDLs) of substances (e.g. Havens & Schelske, 2001; Fakhraei et al., 2014) and implementing ecologically-based approaches for avoiding the need for TMDLs (Hall et al., 2019). As the TMDLs can be required at any time in which the excess occurs (Steinman & Ogdahl, 2015), scientists are not bound to specific time windows for collaborating. Scientific studies can always always be applied to inform other management goals for resolving local, prevalent or nuisance issues (e.g. Latimore & Steen, 2014; Richardson et al., 2012; Song et al., 2016). Overall, the opportunity of engaging scientists in management seems more plausible under the USCWA legislation than the WFD.

4.4 Engagement methods

The fourth survey theme related to efficient methods of collaborating and communicating with lake managers (Figure 5). For scientists interested in becoming more effective collaborative partners, this translates to discussing collaboration challenges and mechanisms with lake managers. Funding was indicated by lake managers in both North America and Europe to be the largest collaboration challenge. One method for addressing the funding shortage for intersectoral collaborations is, as mentioned above, utilizing co-design to optimize both science and management interests (e.g. Heubach & Lambini, 2018). With jointly created projects, establishing management needs and the capacity for science to fulfill those gaps at the project onset can assist in defining and acquiring the necessary funds. With independent scientific research, scientists can also take steps at the beginning of their projects to assess if their findings will address any management needs. This can be facilitated, for example, with grant applications in the European Union now requiring justification on the societal relevance and the foreseen transfer of knowledge of the proposed research (Robinson et al., 2020). In order for co-creation and co-design principles to become operational beyond proposal writing, science organizations may want to change their reward and recognition system beyond current impact factor related metrics (Beck et al., 2019; Nguyen et al., 2019).

While numerous intersectoral projects with their own methods for collaborating have been conducted, not one single approach is suitable for every science-management partnership. Rather, existing methods of frameworks, tools and guidelines can be tailored to suit both the scientific and management parties. For instance, multiple case studies have outlined intersectoral collaborations that utilized frameworks for guiding multisectoral discussions. Examples include the Ecosystem Services Approach (Reyjol et al., 2014), the scenario analysis approach (Laurent et al., 2015) and the UNESCO International Hydrological Programme (Makarigakis & Jimenez-Cisneros, 2019), which all integrate science and management into the framing and discussion of management decision-making.

Both tools and best practices can similarly stimulate intersectoral discussions. Serious games or other social boundary objects that act as mediums for discussion can promote inclusion amongst multiple sectors and instill a common language for knowledge sharing and group learning (Armstrong et al., 2021; Williams, 2015). Best practices can similarly bolster the effectiveness of science-management collaborations such as with intersectoral communications being initiated at the start of the project (Williams, 2015) and having established knowledge management systems for fulfilling research project knowledge transfer (Cvitanovic et al., 2016).

4.5 Future steps

Given the array of challenges anticipated to occur or intensify in the coming years, insight into improving intersectoral collaborations can support effective management planning. While recognizing that the small survey sample size renders a basic initial overview of regional approaches at the lake science-management intersect, the results of this study indicate that there are differences in approaches to and opportunities for science-management collaborations. There are perceived links between the policy legislation that guides management targets and the level of intersectoral collaborations that occur between lake science and management. Further research should explore whether it is policy that dictates the level of intersectoral collaborations that occur (top-down approach) or if the amount of intersectoral collaborations that occur drive the policy that is enacted (bottom-up approach). Drawing from science domains beyond ecology, it seems likely that policy plays an important role in shaping intersectoral partnerships, with e.g the Helsinki Statement on Health in All Policy actively facilitating long-lasting effective intersectoral partnerships (Corbin et al., 2018).

Based on the observed differences in regional manager perceptions, it would be of interest to extend the survey to include larger groups of lake managers and those that are located in regions beyond North America and Europe for comparison. A more extensive survey could further integrate additional factors such as population density and cultural beliefs which can influence management methods (Reynaud & Lanzanova, 2017).

4.6 Conclusion

Concluding, our study suggests that the role of science in lake management differs between North America and Europe. From our analysis, there is a perceived solution for strengthening the role of scientists in decision-making by jointly identifying and tailoring collaboration frameworks. Implementing co-creation principles throughout the decision-making process can create joint ownership of lake challenges and at the same time surmount collaboration challenges such as acquiring sufficient funding.

Supplementary Materials

Appendix 1

Survey for assessing lake manager perspectives on the role of science in decision-making

Survey for Improving Lake Manager and Scientist Dialogue

This 25-question survey distributed by the Netherlands Institute of Ecology (https://nioo.knaw.nl/en) in collaboration with the Global Lakes Ecological Observatory Network (https://gleon.org/) is part of a study on multidisciplinary collaboration for lake health and functioning. The survey is estimated to take 20 minutes. Our aim is to understand the lake management perspective internationally on:

1) challenges affecting lake management,
2) science's role in management,
3) effective communication methods,
4) examples of successful collaborations and
5) planning for climate change and extreme climatic events.

The questions in this survey focus on the opinions and insights of lake managers regarding their experiences working with scientists (biological, physical, chemical, ecological and social disciplines) during normal working circumstances (before the global covid-19 situation). Your responses will help advance understanding amongst scientists on effective communication approaches and, ultimately, support future collaborations to benefit our lake ecosystems. We would like to invite all lake managers tasked with the development or implementation of management actions to participate in this study.

Below is the Data Privacy Statement and the Terms of Agreements for participation. Please read through the information before answering Question 1 and clicking "Next" to begin the survey.

1

Data Privacy Statement

At the Netherlands Institute of Ecology ("NIOO"), we employ steps to ensure the professional handling of all data that result from social science studies. We are therefore providing information detailing the purpose of this study, the method for gathering data, the use(s) of gathered data and the process of data storage.

How does my participation support this research project?

Following the aim of this project, we would like to gather the insights and experiences of water managers on:

- the current challenges affecting management of the ecosystems,
- the role of science in lake management,
- method(s) of effective science communication(s) and
- planning for climate change and extreme climatic events.

Your responses to the survey questions will offer valuable insights into these topic areas and assist in promoting more collaborative science with the aim of betterment of our lake ecosystems. As we aim to acquire data from lake managers and lake management organizations around the globe and at various institutional levels, every completed survey will support this goal.

Voluntary participation

Your participation in this study is voluntary. If you wish to withdraw from the study, you maintain the right to be forgotten under the European Union's General Data Protection Regulation (GDPR). Your personal and identifying data will be removed from the data set if you withdraw before the article is submitted for publishing. Once your data has been published in a peer-reviewed journal, your data cannot be removed. All data included in the published article(s) will be anonymized (see: "To what extent is my participation confidential?").

What happens if I participate?

We are gathering input directly from lake managers about their experiences regarding challenges with lake systems and about interdisciplinary communication methods. Participation in this study is comprised of filling out the 25 question online survey about your experience(s). Your responses to the survey questions will provide data to develop recommendations and tools for improving the effectivity of communication.

Advantages and disadvantages of participation

There are no foreseen disadvantages to participating in this study. Any results arising from the surveys will be used in expanding and honing science communication for the improvement of interdisciplinary collaboration. The time for participation in the study is estimated at 20 minutes (for completing the survey).

To what extent is my participation confidential?
The NIOO practices an Open Access policy in which all published data will be accessible to the public. All sensitive data gathered during research will be protected through anonymization of personal information, such as name, employment position and contact information. The online platform Surveymonkey, which is being utilized for the survey dissemination, has an option to not collect IP addresses of survey respondents ("Anonymous mode"). This option has been enabled as a method for preventing personal data from being collected.

We are obliged to archive your research data. Participation in this study implies permission to do so. With this, we follow the relevant regulations, such as the GDPR and the NIOO's best management practice guidelines. During the research project, your full data are only accessible to researchers from the NIOO that are participating in the SMAC project. Other members of the SMAC project will have access to the anonymized version of the data. You can always contact the researchers if you wish to have access to your data.

Written and verbal communications about this survey data (as outlined in the following section) will preserve the confidentiality of participants.

What happens with the results of this study?
Data will be used to develop recommendations for enhancing communication effectivity and as guidelines for creating communication tools. The results of these surveys will be statistically analyzed to identify any significant pattern in the responses provided. Your anonymized responses will be summarized in a scientific article that will be published in a peer-reviewed journal. Other communications about the study, such as in verbal discussions, presentations and in other scientific publications, can also include the anonymized results.

Who should I contact if I want more details on this study?
If you have any questions or want more information, you can contact Maggie Armstrong (see below for contact details) or the researcher with whom you've been in contact. If you wish to learn more on the data management policy of the NIOO, you can contact the Data Protection Officer at P.vandenBerg@nioo.knaw.nl and the Privacy Coordinator at s.bekker@nioo.knaw.nl.

Maggie Armstrong
Netherlands Institute of Ecology
MANTEL@nioo.knaw.nl
+31 (0)317-473400

Terms of Agreement
The terms of agreement to participation in the study include all of the following. By agreeing to participate in the study, you acknowledge and agree to the following:
· I have received the information on the goals of the study "SMAC," and I have read and understood this information.
· I have had sufficient time to consider my participation. I have been able to ask questions. These questions have been satisfactorily answered.
· I grant permission for participation in this study.
· I know participation in this study is voluntary, and that I can withdraw my permission during the research without having to motivate that choice.
· I assent to using my research data as described in the information letter under the header 'To what extent is my participation confidential'?
· I understand that the information obtained from this research will be saved in a protected environment.

* 1. I have read the above Data Privacy Statement and the Terms of Agreement. I acknowledge the terms for participating in this study.

◯ Yes

◯ No

Survey for Improving Lake Manager and Scientist Dialogue

2. What type of organization are you part of?
If multiple options are applicable, please select your main organization type

- ◯ Lake management organization
- ◯ Academic institute
- ◯ Research institute
- ◯ Governmental organization
- ◯ Consultancy firm
- ◯ Non-profit or non-governmental organization
- ◯ Other (please specify)

3. In what country are you located?
If multiple countries are applicable, please enter your main country of operation/work

4. What is your role in the organization?
Select all options that apply

- ☐ Manager
- ☐ Scientist
- ☐ Other (please specify)

5. Do you have a science background?
(For example: a certified degree (Bachelors, Masters, PhD), career experience, certified training course, etc. in a science-related field)

- ◯ No
- ◯ Yes, I have the following background:

4

6. At what scale does your organization operate?

Select all options that apply

- ☐ Individual water body
- ☐ Local
  (for example: township area, small natural reserve area, etc.)
- ☐ Regional
  (for example: multiple township areas, large national park, etc.)
- ☐ Watershed/Catchment
- ☐ State/Province
- ☐ Multiple States/Provinces
- ☐ National
- ☐ International
- ☐ Global

7. What are your main management goals?

Select all options that apply

- ☐ Water quality
- ☐ Water quantity
- ☐ Biodiversity/Conservation
- ☐ Drinking water provision
- ☐ Sanitation
- ☐ Commercial fisheries
- ☐ Recreation
- ☐ Other (please specify)

8. What are your biggest management challenges?

Please select up to 5 options that apply to your management organization

- ☐ Industrial pollution
- ☐ Water withdrawal(s)
- ☐ Urbanization
- ☐ Extreme climatic events
  (for example: heatwaves, droughts, floods)
- ☐ Habitat degradation
- ☐ Climate change
- ☐ Algal blooms (harmful, nuisance)
- ☐ Eutrophication
- ☐ Biodiversity loss
- ☐ Invasive species
- ☐ Tourism/Recreation impacts
- ☐ Water level management
- ☐ Human pathogens
  (for example: pathogen exposure when swimming or drinking, etc.)
- ☐ Sanitation
  (for example: wastewater treatment plant outflow quality, sewage overflows, septic system leakages, etc.)
- ☐ Water rights
  (for example: transboundary water allocation between jurisdictions)
- ☐ Other (please specify)

9. What ecosystem services (here defined as "the social and economic values/benefits that humans receive from ecosystems") provided from the lake system(s) in your management area are used by citizens/stakeholders/visitors?

Select all options that apply

- ☐ Drinking water source
- ☐ Irrigation water source
- ☐ Food material
  (for example: fish, plants, etc.)
- ☐ Goods materials
  (for example: clothing, construction, etc.)
- ☐ Species habitat
- ☐ Biodiversity
- ☐ Hydropower

- [ ] Bioremediation of contaminants
- [ ] Water filtration
- [ ] Climate regulation
- [ ] Hydrologic flow regulation
- [ ] Flood control
- [ ] In-water recreation
  (for example: swimming, water skiing, fishing, etc.)
- [ ] Shoreline recreation
  (for example: beach access, walking trails, fishing, etc.)
- [ ] Community venue
  (for example: community gathering location, etc.)
- [ ] Tourism industry
  (for example: provides jobs, economy inflow)
- [ ] Health benefits
  (for example: "blue space" retreat for reducing stress)
- [ ] Aesthetic values
  (for example: visually attractive site, increase in property values)
- [ ] Cultural and heritage significance
  (for example: sense of place, cultural identity)
- [ ] Sacred values
  (for example: religious location)
- [ ] Education
  (for example: school trips, summer camps, citizen science programs, etc.)
- [ ] Research
  (for example: experiment site, sampling location, etc.)
- [ ] Other (please specify)

10. What is the current role of science in your management approach?
Select all options that apply

- [ ] Assess the effectiveness of a management action towards achieving the specified goal
- [ ] Provide suggestions for different methods/tools that could be used in management actions
- [ ] Continue improving the methods/tools that are used in lake remediation or monitoring, which lake managers can use in their systems
- [ ] Offer research insights into the wider impacts that a specific management action could have on the lake system
- [ ] Provide models and projections on the future challenges that will hinder the lake system and its provisioning of ecosystem services
- [ ] Identify contaminant thresholds *(for example: nutrient runoff from catchments, water quality standards, etc.)*
- [ ] Other (please specify)

11. What do you think the role of science in your management approach *should* be?
Select all options that apply

- [ ] Assess the effectiveness of a management actions towards achieving the specified goal
- [ ] Provide suggestions for different methods/tools that could be used in management actions
- [ ] Continue improving the methods/tools that are used in lake remediation or monitoring, which lake managers can use in their systems
- [ ] Offer research insights into the wider impacts that a specific management action could have on the lake system
- [ ] Provide models and projections on the future challenges that will hinder the lake system and its provisioning of ecosystem services
- [ ] Identify contaminant thresholds *(for example: nutrient runoff from catchments, water quality standards, etc.)*
- [ ] Other (please specify)

12. What scientific collaborators and/or sources do you work with?
Select all options that apply

- ☐ Scientists on the management team (or within your organization)
- ☐ Scientists available for consultation
  (for example: contract out the work to external organizations)
- ☐ Network of scientific groups
  (for example: connections to individuals in other scientific organizations that can be leveraged for advice, etc.)
- ☐ Scientific reports for guiding aspects of management
- ☐ Scientific data from databases or publications
  (for example: data from laboratory experiments, field experiments or field observations)
- ☐ Self-gathered scientific data (you collect the data yourself)
- ☐ Citizen science data from projects, databases or publications
- ☐ None
- ☐ Other (please specify)

13. Describe the current gaps in available research that could support your management priorities.
(For example: evidence that policy is working, lack of analysis results, support with applying or disproving methods, etc.)

14. What have been the biggest challenges when communicating/collaborating with scientists?

Please select up to 5 options that apply to you and your organization

- ☐ Determining which scientist(s) to contact
  (for example: identifying persons with relevant knowledge, research interests, etc.)
- ☐ Establishing contact with scientist(s)
- ☐ Availability of scientists
  (for example: scientists seem willing to help but are too busy or are located too far from your site)
- ☐ Engaging scientist(s) with a practical problem that requires an applied solution rather than theoretical research
  (for example: defining the applied research requirement during initial discussions, specifying the connection of theoretical research to practical applications, interest the scientists in an applied research study, etc.)
- ☐ Defining or communicating the management goals
  (for example: stakeholder interests and involvement, management requirements and constraints, etc.)
- ☐ Establishing a collaborative research goal
  (for example: reconciling scientist research interest(s) with the management goals)
- ☐ Finding data relevant to the management situation
- ☐ Language barriers due to jargon
  (for example: terminology, acronyms, etc.)
- ☐ Finding funding to support the scientific collaboration
- ☐ On-time delivery of deliverables according to legislative or project schedule
- ☐ Other (please specify)

15. What communication method has been effective when collaborating with scientists?
Select all options that apply

- ☐ Meeting in person at the office
- ☐ Meeting in person at public gatherings such as conferences, town halls, etc.
- ☐ Meeting in person at the field site
- ☐ Conversing over the phone
- ☐ Conversing electronically with email, instant messaging, etc.
- ☐ Gathering perspectives electronically with surveys
- ☐ The methods are unimportant, regular communication is the key
- ☐ No outside communication is necessary as scientists are part of your management organization
- ☐ No outside communication is necessary as your organization has a manager working on the scientific tasks as well as the management tasks
- ☐ No methods have been effective
- ☐ Other (please specify)

16. Do you include scientists (internal and external to your organization) in the management discussions that take place within your organization?
(For example: by asking scientists for advice, protocols, have them carry out part of the work, etc.)

- ○ No, we do not include scientists in these conversations
- ○ Yes, we include scientists in management discussions
- ○ Yes, I am a scientist and I am included in management discussions

Space for further explanation of "yes" responses is available here
(For example: if scientists are always included in these discussions, if scientists are included in management discussions for specific issues, if scientist inclusion depends on the annual budget, etc.)

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17. If you do include scientists in management discussions, during what parts of the discussion are they included?

Select all options that apply

- [ ] Not applicable - we do not include scientists in management discussions
- [ ] Before the discussions (get advice on lake issues that should be addressed, ideas on how to manage issues, etc.)
- [ ] Identifying main management issues to be addressed
- [ ] Prioritizing and establishing management plan goal(s)
- [ ] Deciding management actions to be taken
- [ ] Planning implementation of management action(s)
- [ ] Assessing impact of management action(s)
- [ ] Other (please specify)

18. Do you include internal or external scientists in the management discussions that take place with stakeholders (here defined as "individuals or groups that utilize the services of a lake")?

(For example: by asking scientists for advice, protocols, have them carry out part of the work, etc.)

- ◯ Not applicable because my organization does not engage stakeholders
- ◯ No, we do not include scientists in these conversations
- ◯ Yes, we include scientists in management/stakeholder discussions
- ◯ Yes, I am a scientist and I am included in management/stakeholder discussions

Space for further explanation of "yes" responses is available here
(For example: if scientists are always included in these discussions, if scientists are included in stakeholder discussions for specific issues, if scientist inclusion depends on budget availability, etc.)

19. If you do include scientists in stakeholder discussions, during what parts of the discussion are they included?

Select all options that apply

- ☐ Not applicable - we do not include scientists in stakeholder discussions or we do not have stakeholder discussions
- ☐ Before the discussions (get advice on lake issues that should be addressed, ideas on how to manage issues, etc.)
- ☐ Identifying main management issues to be addressed
- ☐ Prioritizing and establishing management plan goal(s)
- ☐ Deciding management actions to be taken
- ☐ Planning implementation of management action(s)
- ☐ Assessing impact of management action(s)
- ☐ Other (please specify)

20. At what point do you think scientists *should* be included in management discussions within your organization?

Select all options that apply

- ☐ Not applicable - we do not include scientists in management discussions
- ☐ Before the discussions (get advice on lake issues that should be addressed, ideas on how to manage issues, etc.)
- ☐ Identifying main management issues to be addressed
- ☐ Prioritizing and establishing management plan goal(s)
- ☐ Deciding management actions to be taken
- ☐ Planning implementation of management action(s)
- ☐ Assessing impact of management action(s)
- ☐ Other (please specify)

21. At what point do you think scientists *should* be included in management discussions with stakeholders?
Select all options that apply

- ☐ Not applicable - we do not include scientists in stakeholder discussions or we do not have stakeholder discussions
- ☐ Before the discussions (get advice on lake issues that should be addressed, ideas on how to manage issues, etc.)
- ☐ Identifying main management issues to be addressed
- ☐ Prioritizing and establishing management plan goal(s)
- ☐ Deciding management actions to be taken
- ☐ Planning implementation of management action(s)
- ☐ Assessing impact of management action(s)
- ☐ Other (please specify)

22. How can scientists make their research more accessible to managers?
Please select up to 5 options that apply to you and your organization

- ☐ Use less jargon words and phrases
  (for example: use common terms to make applied messages for managers, stakeholders, etc.)
- ☐ Seek manager input when framing research questions
- ☐ Collaborate with stakeholders to guide research questions
- ☐ Have Open Access scientific publications (articles are free-of-charge)
- ☐ Communicate results in a non-scientific article format
  (for example: reports, policy brief, newsletter, press release, etc. in addition to the scientific articles)
- ☐ Communicate information in a non-report format
  (for example: serious games, diagrams, pamphlets, presentations, etc.)
- ☐ Make models and other tools more user-friendly
- ☐ Have conversations about approaches, goals and methods more frequently
- ☐ Involve managers in education programs and workshops
  (for example: Masters and PhD programs, certification programs, public lectures, etc.)
- ☐ Work with Public relations/Communication specialists to develop messages
- ☐ Other (please specify)

23. Do you have an example of when improved communication or engagement methods were successfully implemented/practiced during collaborations with scientists? Please state the ecosystem name and location, a brief summary of the example and the involved organizations.
(For example: asking local stakeholders for their research questions for a lake)

24. Do your management plans include preparations/adjustments for climate change scenarios in lake ecosystems?
(For example: present and future changes in average temperature and precipitation)

- ◯ No
- ◯ Yes, we plan adaptive measures to minimize the effects of climate change in lake(s) before the future projected trends occur
- ◯ Yes, we are planning reactive measures to mitigate the effects of climate change in lake(s)
- ◯ Unknown

If you answered "yes" or if climate change is managed in a way different than expressed above, space is available here to explain
(For example: types of measures implemented, types of plans created, etc.)

25. Do your management plans include preparations/adjustments for extreme climatic events in lake ecosystems?

(For example: present and future changes in the extreme ends of heat/cold waves, precipitation, drought, wind, etc.)

- ◯ No
- ◯ Yes, we plan adaptive measures to minimize the effects of extreme climatic events in lake(s) before the event takes place
- ◯ Yes, we plan reactive measures to mitigate the effects of extreme climatic events in lake(s) after the event takes place
- ◯ Unknown

If you answered "yes" or if extreme climatic events are managed in a way different than expressed above, space is available here to explain

(For example: types of measures implemented, types of plans created, etc.)

Survey for Improving Lake Manager and Scientist Dialogue

Survey Completed

Thank you for participating in this survey. Your responses will assist with identifying ways for scientists to begin communicating more effectively during collaborations with lake managers.

If you have any questions, comments and suggestions about this survey and the research study, they can be sent to: MANTEL@nioo.knaw.nl

If you would like to receive notification(s) about or a weblink to the publication(s) that result from this project, send an email stating your interest to MANTEL@nioo.knaw.nl. The lead researcher will provide the requested information when it becomes available.

Appendix 2

Table 1: Overview of survey respondent demographic information for North America and Europe

	North America		Europe
	United States	Canada	
	N = 43	N = 4	N = 15
Organization			
Academic institute	2	0	3
Consultancy firm	2	0	0
Government organization	19	1	5
Lake management organization	12	1	4
Non-profit organization	7	1	0
Research institute	1	0	1
Other	0	1	2
Position			
Manager	11	1	6
Manager/Scientist	10	0	0
Scientist	9	0	5
Other	13	3	4
Science Background			
Degree	36	3	13
License	2	0	0
Experience	13	0	3
None	4	1	0
Scale			
Water Body	14	1	3
Local	16	0	4
Regional	16	1	7
Watershed	13	2	4
State/Province	22	1	3
Multiple States/Provinces	6	0	2
National	2	0	6
International	2	0	3
Global	0	0	0

Appendix 3

Table 2: Overview of participant demographic information for Water Framework Directive interviews

	Interview Participants
	N = 9
Country	
The Netherlands	5
Spain	2
United Kingdom	2
Organization	
Government organization	7
Industry organization	1
Management organization	1
Role	
Designated water authority	7
Partner organization	2

General Discussion

1. Extreme pressures on the biosphere

The shifting baseline of extreme climatic event ("ECE") intensity and frequency in the climate projections of coming decades hints at a future full of "unprecedented," "unprepared," and "overwhelming." There is an argument to be made that, with the extensive uses and values of freshwater to disparate stakeholders and groups, all people have a vested interest in the quality and quantity of water. Lakes in particular offer a setting that permits many communities and visitors with an access point to the hydrosphere. The management and stewardship of these systems is complex as, in addition to ECE concerns, there is a long history of system degradation due to human actions. Lakes can act as "sentinel" within the catchment, implying that all past, present and likely future pressures from press (e.g. urbanization) and pulse (e.g. spills of pollutants) events can culminate in impaired ecosystem functionality. With many freshwater lakes globally already imperiled by existing pressures (Heino et al., 2021), the projected shifts in ECEs could exacerbate these stressors (Field et al., 2014). Further degradation of lakes due to climatic-based shifts is a concern for all human communities, especially as the compromising of lake functions can hinder the ability of these systems to provide the various ecosystem services on which our communities depend (Heino et al., 2021). With scientifically-supported understanding that lakes are not capable of withstanding all of these pressures indefinitely (e.g. tipping points, Martin et al., 2020; alternative stable states, Ibelings et al., 2007), the threat of ecosystem collapse should be a driving force in pushing for informed, effective management interventions.

Tracing extreme pressures (climatic and societal) from occurrence to effect will be significant in understanding exactly how water systems will be affected. This insight must then be taken further to assess how management interventions can address the underlying pressures to system (mitigation) and to begin limiting the source of the pressures (prevention). Chapters one through four constituting the original research of this thesis therefore trace the cause-effect relationship from 1) the occurrence of extreme event(s) to 2) their implications on ecosystem functions to 3) the resulting effect on ecosystem service provisioning and 4) the overall implications that intersectoral collaborations could have on ecosystem remediation.

Chapter one on the implications of combined extreme stressors on an artificial phytoplankton community dynamic traced the projected extreme scenarios with its direct applications to ecosystem functions. **Chapter two** with the observed effects on a non-climatic-based extreme event from the COVID anthropause illustrated the connections between an extreme event, its effects on ecosystem functions, the subsequent implications on the demand for and provisions of ecosystem services as well as guidelines for management. **Chapter three** on the Flipping Lakes game directly connects the implications of extreme events on both the functions and services of lake systems on the surface "level" of this tool. On a deeper level, the game exemplifies a method for establishing communication between science and management as well as offering a tool to be shaped for broader discussions with stakeholders and other parties pertinent to lake-oriented decision-making. **Chapter four** focused on defining the challenges affecting intersectoral collaborations between science and management sectors, which broadly incorporates the cause-effect relationships of scientific knowledge informing management decision-making. Each of these chapters employed different methodologies to assess research questions related to the overarching cause-effect relationship. These methodologies are discussed throughout this section. Additionally, a table summarizing the strengths and weaknesses of each of these methods is presented at the end of this section (Table 1).

2. Extreme pressures on ecosystem functions

In **chapter one**, the microcosm experiment did not exemplify the widely-held scientific theory that the co-occurrence of multiple ECEs or of one ECE with another pressure (e.g. average climate change or anthropogenic land use changes) will create scenarios with additive, or multiplicative effects (e.g. Jackson et al., 2016; Ekvall et al., 2013; Folt et al., 1999; Kosten et al., 2012). Common rhetoric around the implications and concerns surrounding coinciding lake pressures, especially ECEs, alludes to a general, widespread theory that such scenarios have additive or multiplicative effects (or effects that are "greater than their individual parts") on already chronically degraded lake systems. With ECEs, it is also assumed that the impacts of such events will be disproportionately long in comparison to the event's duration. This driving assumption has helped to advance insights in the impacts of ECEs in recent years. In the experiment described in **chapter one**, our results contradicted this widely-held hypothesis by demonstrating that algal communities did not respond as expected to simultaneous short-lived (precipitation) and long-term (temperature) climatic events in the microcosm system. This same result – of coinciding events having negating, rather than compounding, effects – has been observed in other controlled experiments. For instance, the mesocosms exposed to full-factorial temperature, nutrient and rainfall treatments had resulted in some unexpected antagonistic interactions, demonstrating the possibility for "ecological surprises" to happen (Richardson et al., 2019). This was similarly found in the Bergkemper et al. (2018) experiment with temperature, light and nutrient treatments not resulting in anticipated positive synergistic effects.

There is a need to understand the mechanisms behind ECE effects further as, with the general assumptions not holding true in simulated situations, it could similarly not be applicable in lake systems (e.g. Jackson et al., 2016). Continuing to assess the implication of coinciding pressures within a simulated system can be advantageous if the parameters of the pressures are tested incrementally. For example, holding all parameters of coinciding stressors constant except for one (e.g. incrementally adjusting the water temperature between the replications or experiment trials) can offer a chance to determine thresholds for algal responses, such as with dose-response relationships. This can account for the diversity of pressures affecting lake systems by incorporating a combination of short-term stressors ("pulse" events, e.g. heatwaves, storms) and long-term stressors ("press" events; e.g. droughts, eutrophication; Bender et al., 1984), thereby yielding realistic insights into a future with more coinciding stressors. Studies can begin at a microcosm or mesocosm scale to set the tipping point thresholds before extrapolating the findings to larger enclosures. The "cosm" study findings can also inform model simulation for analyzing lake-scale effects or could be used to evaluate lake monitoring data for correlations between the parameter thresholds with algal responses. For example, results from controlled laboratory studies can inform the calibration of lake models (e.g. PCLake+) in order to support the development of more realistic scenarios.

3. Extreme pressures in a broader context

ECEs are not the only abrupt, highly disruptive force that is affecting lakes and other surface water systems. More direct human influences on water bodies can be as impactful as that of climate averages and extremes. Anthropogenic influences extend past the usual suspects of land use change (urbanization and agricultural intensification) to also include shifts in typical patterns of basic human behaviors. **Chapter two** presented an overview of how the COVID-19 pandemic affected urban water systems. Specifically, the COVID-19 anthropause bore witness to the sheer scale of influence that occurs when enough people abruptly change their lifestyles. The cessation of specific activities (in this case related to travel or public gatherings) and the re-direction towards other activities (for example, adopting or increasing hobbies such as recreational fishing or shoreline strolls) caused alleviation for some systems and stress on others. In a world where both climatic extremes and societal pressures (such as pandemics) are projected to become more likely, it is paramount that we understand the mechanisms behind the effect that these individual and combined stressors have on freshwater systems. Management interventions aimed at maintaining or improving lake health must therefore be able to continue under these emerging, disruptive (and likely persistent) challenges.

4. Extreme pressures and intersectoral management

4.1 Developing informed plans

The persisting and global challenges when it comes to lake systems (e.g. eutrophication, biodiversity loss, etc.) can be interpreted as a need for a paradigm shift in how we perceive and address pressures. For example, from **chapter one** there is little doubt that the increased frequency and intensity of the various pressures affecting lake systems will contribute to the chronic stress being exerted on the water bodies. However, if the effects of coinciding events cancel out or diminish each other, we can make adjustments in intervening management plans to capitalize on the self-imposed mitigation. Still, having a thorough understanding of how the mechanisms are interacting will be pertinent for planning, especially in scenarios where coinciding pressures result in interactions less than the sum of their individual effects. Intervening with only one of the coinciding pressures could therefore disrupt this the mitigating effect and instead result in the non-addressed pressure exerting its full influence on the system (e.g. Christensen et al., 2006). Given the ominous outlook of ECEs and combined pressures along with the uncertainty as to how these scenarios will affect lakes, a change in status quo is warranted.

Evaluating how scientists and lake managers interact when researching and managing lakes, respectively, can help provide valuable insights into how the different sectors and their knowledge can be integrated for creating informed decision-making (e.g. Stoffels et al., 2021). In particular, combining knowledge across professional sectors can begin addressing ECEs and other coinciding lake pressures (e.g. Hegger & Dieperink, 2015). **Chapter four** was based on the survey of lake manager perspectives regarding the roles that science information and scientists themselves fulfill within lake management approaches and how these roles could be expanded. Comparisons between regions (North America and Europe) illustrated that different geographic areas can have varying management structures and deviating (inter)national policies, necessitating the understanding of how lake management structure works in order to determine optimal science-management intersectoral collaborations. For instance, the recent European Union Water Framework Directive ("WFD") has the advantage of decades of knowledge and insights when the policy was formed, thereby offering the chance for science to be well-integrated into the policy's design (Voulvoulis et al., 2017). This was a chance well-utilized as the WFD's calibration process and reference conditions are grounded in extensive scientific knowledge (Poikane et al., 2015). As a result, all this information in the initial stages of the policy creation may have led to managers not needing scientists as extensively throughout the subsequent cycles. There is, of course, still room for the science to assist with the day-to-day management as well as in helping develop the Programme of Measures, but European lake managers did not indicate the need for extending or deepening intersectoral collaborations further than they are at present. In comparison, the older United States Clean Water Act and the

Canada Water Act were not created based on holistic scientific approaches which have been more commonly applied in recent decades (e.g. Boyd, 2000), leaving opportunities for scientists to work alongside managers now to apply knowledge. Expanding such a comparison to include other regions with different guiding water policies could continue elaborating the opportunities for scientists to become more involved in lake management.

4.2 Distilling disruption knowledge

Abrupt and significant events can present an acute stressor on lake systems. From **chapter two**, the COVID-19 anthropause was an undesired but opportunistic case study of shifted human behaviors and their subsequent pressures on the biosphere. This disruption of typical trends offered abundant insight into the functions and values of water systems in our highly interconnected world. One lesson distilled from the anthropause is that water systems are capable of quick recovery when given an uninterrupted opportunity to self-heal. This was evidenced with the rapid increase of water clarity in highly traversed canal systems (e.g. Braga et al., 2020). Additionally, the removal of visitors in some parks and beaches led to habitat recovery (e.g. Smith et al., 2021). A second lesson was that some of the observed recovery was not permanent, as resumed human activities once again caused degradation in the system (Zielinski & Botero, 2020). Thus, it is worthwhile to observe the changes that happened, acknowledge the importance of allowing systems a recovery period and adapt management approaches that support such undisturbed recovery.

5. Extreme pressures and community involvement

The crux of freshwater being an excessively utilized resource for both basic life necessities and for commodities is that there are many “hands” tampering with the health of ecosystems, both directly and indirectly. One significant undertaking necessary for optimal, pointed management of systems is the comprehensive understanding of how water is being used, who is placing demands upon the system and where the inevitable pressures are coming from. The DPSIR framework, for instance, highlights the connection of drivers-pressures-states-impacts-responses in order to illustrate the interconnectivity of the cause-effect relationships throughout ecosystems and society (Tscherning et al., 2012). This insight is foundational to developing and implementing informed interventions that will address detriments to ecosystems. Based on this foundation, then, is a second undertaking that can reduce the onus of this task on management organizations and instead spread the responsibility amongst the numerous “players” (and their hands). Intersectoral “co-creation” of projects through the active participation and leadership of lake stakeholders in management initiatives can pave the way for achieving holistic management of systems (e.g. Medema et al., 2016).

There are abundant opportunities to expand the available knowledge of water systems through engagement of overlooked groups or nontraditional science approaches. This includes utilizing existing knowledge of these groups as well as increasing the scientific literacy of interested citizens. In addition to the Flipping Lakes serious game (as described in **chapter three**), a second game was created over the duration of this PhD. This game was based on the “Benefit Game,” created by Dr. Elisa Ruijgrok, which is a tritet (i.e. three card) card game aimed at improving players’ skills with tracing cause-effect relationships (Figure 1). A lake-oriented version of this game (“The Water Management Benefit Game”) was constructed to assist in defining how management actions (“measure”) affect a parameter (“quality”) of water systems. In turn, the connection was also traced to how the management measure and lake quality affect the ecosystem services ("benefits") provided by the water system. This tool is one example of how stakeholders can receive readily-accessible training to enhance their environmental literacy. In turn, making an "even playing field" by training and including stakeholders can lead to the incorporation of their knowledge into management discussions and decision-making.

Figure 1: Example of Lake Management Benefit Game cards, front and back sides. Red card are the "Action" cards, yellow cards are the "Quality" cards and green cards are the "Benefits" cards.

5.1 Existing knowledge sources

5.1.1 Local, indigenous and stakeholder knowledge

Professionally trained lake managers and scientists may have a firm understanding of their field and how knowledge can be applied for managing and researching lake systems, but the water body's story is incomplete if information is missing about how humans have been and are currently using the lake. As is the case with many ecosystems, lakes can be defined as "socio-ecological systems" as these ecosystems are entwined with both ecological-based processes as well as those of processes grounded in society. Understanding how lakes are being affected by, and in turn are influencing, the various cause-effect relationships between ecological and societal processes is important for developing management plans. Therefore, gathering knowledge from a diverse group of stakeholders is pertinent for mapping out these cause-effect chains. Firsthand knowledge from the people that live with and use the lake systems can be significant sources of information (Hakkarainen et al., 2021), with co-creation processes allowing the different actors to appreciate epistemological differences. From outlining the user groups within the system to detailing the history of the system, personal accounts of the residents can "fill in" gaps about how the lake is integrated into the local community and economy (e.g. Ogada et al., 2017). Knowledge about historical management practices and interventions can also enlighten management options that may be more suitable to addressing the system's challenges, such as with re-introducing indigenous management practices in areas where it used to be effective (e.g. Knapp et al., 2019). Going further, having an intimate understanding of how the community and lake system interact can permit a deeper understanding of potential conflicts, future resource challenges and ultimately a more informed perspective for considering future management actions (e.g. Díaz et al., 2018).

5.1.2 Citizen science

In **chapter four**, sources of scientific knowledge (theme two of the survey) were asked of the lake manager survey respondents. Within the comparison of North American and European respondents, one pathway of knowledge acquisition that deviated significantly was the use of citizen science. The disparity of acknowledged citizen science applications in management (with North America having a higher response rate for utilizing citizen science) can indicate a distinct difference in societal involvement in lake management between the two regions. In general, citizen science is recognized for its capacity to support target fulfillment such as with the Sustainable Development Goals (Shulla et al., 2020). Applications of this method have been key in not only populating large datasets (Poisson et al., 2020) but also informing management actions (e.g. Vincent et al., 2017). Distinguished projects in North America and Europe have been coordinated by both scientist groups (e.g. Seelen et al., 2019; Weyhenmeyer et al., 2017) and national agencies (e.g. Dosemagen & Parker, 2019; Rubio-Iglesias et al., 2020). The impetus behind less frequent utilization of citizen science data or methods could be due to uncertainties stemming from the field's newness (Thornhill et al., 2016), such as with disparities of professionally and non-professionally gathered data and the time commitment for training volunteers (McGoff et al., 2017). This could also, to an extent, be due to gatekeeping of scientific information, such as through paper paywalls, data inaccessibility and the peer-review process (e.g. ElSabry, 2017; Hampton et al., 2015), which can foster the general public's distrust in the information being gathered and provided. Yet, an interviewed European manager stated that local communities can be a driving force for rehabilitation projects, especially when stakeholders are involved in the planning and implementation. Citizens are a source of under-tapped potential for environmental management with explicitly defined projects (e.g. McKinley et al., 2017). Further, the incorporation of citizens in science research and associated lake initiatives could inform communities on existing lake challenges and mitigation practices. In turn, first-hand knowledge from involvement could influence communities to undertake more sustainable, nature-friendly practices within their public and personal spaces (e.g. Kollmuss & Agyeman, 2002). Additionally, the involvement of citizens in management planning and the transparent sharing of information can lead to the public supporting (or demanding) the funding or implementation of mitigation projects.

5.2 Community scientific literacy

Informed citizens can provide a wealth of information on the lake system, as evidenced with incorporating local knowledge into the intersectoral management approaches along with integrating citizens into science initiatives. There are more opportunities to include the public in lake-related endeavors as the balance of the population has potential that is yet untapped. Spurring on the community's engagement with lake research, management and monitoring can simply be a matter of increasing the population's knowledge about the system and its challenges. For instance, people could simply be unaware of what is happening in the system and therefore not know that interventions need to be taken. Additionally, semi-aware citizens could know that the lake is being pressured and that something needs to be done, but not feel capable or empowered to be able to do something themselves. Establishing education campaigns to enhance scientific literacy of the non-scientist, non-management and non-involved portion of society can potentially boost the number of people actively invested in the well-being of lakes (and similar freshwater systems). These can include, for instance, interactive educational tools, non-traditional information dissemination and leveraging environmentally-focused events.

5.2.1 Serious games

"Boundary objects" encapsulate a range of objects that can assist in explaining concepts (e.g. O'Flynn et al., 2011). One such tool includes serious games, which use common, understandable rules of engagement typical of board or computer games in order to transmit information about a complex topic (Jean et al., 2018). In comparison to other boundary objects such as interactive group mapping, the setting created through a game is familiar to many people, requires little technical knowledge to engage with it and is simple enough to use that the underlying concepts behind the educational tool can be gleaned. In **chapter three**, the creation and applications of the serious game "Flipping Lakes" was outlined.

One of the unique characteristics of Flipping Lakes in comparison to many recent serious games was the decision to make the tool as a board game rather than an online game. There are perceived benefits to this, such as the in-person interactions amongst players that the game fosters and all of the further values that such interactions can promote. (While the COVID-19 pandemic has hindered the opportunity for many in-person interactions throughout the past few years, it has also re-established the importance and value that such interactions can have when responsibly and safely conducted.) Additionally, the in-person interactions with game moderators permitted real-time discussions about the game's underlying theories and lessons, thereby beginning the process of increasing players' scientific literacy. Ultimately, the use of the serious game was a welcoming and accessible method of starting discussions. During the trial runs with citizens, university students and administration, the majority of participants were open to using the tool, occasionally displaying curiosity for the scientific, managerial and economic aspects that the game's scenario was founded on.

In addition to the board game format of the tool, the engagement of non-scientific audience with the complex scientific and management concepts was eased through the game's view of lakes through an ecosystem services perspective and simplified healthy/unhealthy state tradeoff, which provided a platform that is understandable and accessible to many non-science and non-management groups. The conditions for service provisioning; implications of anthropogenic, climatic and implicit pressures; and the reasoning for management interventions can be more easily discussed and planned through this context. Particularly with many of the services being dependent upon lake functions and states, this is an ideal bridge between the science of lake health, the economics of human investment and the management that oversees it all.

Flexibility in applying serious games, such as Flipping Lakes, permits multiple uses of the game for involving citizens in lake-related endeavors (e.g. Jean et al., 2018). Aside from the basic enhancement of scientific literacy that is the game's primary objective, there are additional ways in which the game can be used as a bridge between lake professionals and invested citizens. We see potential in using the game for 1) simulating problems in real water catchments, 2) for visually explaining the state of the catchment's uses and pressures and 3) for simulating potential management interventions plans with their potential impact on catchments (e.g Becu et al., 2017). Even with the more technical nature of these secondary game applications and objectives, it is still due to the basic nature of the tool as a game with customizable boards that it can maintain the ease of engaging citizens; rather than a complex tool, the discussion participants will see an accessible game that simplifies and symbolizes problems rather than using a difficult computer model or other inaccessible medium.

Using boundary objects to bring stakeholders and citizens to the discussion table (such as with "Flipping Lakes" and "The Water Management Benefit Game") needs to be highlighted for its effectiveness in broadening intersectoral approaches to addressing lake challenges and solutions. To begin with, the creation of boundary objects needs to be recognized as a valid and effective scholarly output within the scientific community. Presently, the structure of academia rewards behavior that promotes the publishing of peer-reviewed papers while many efforts at outreach and alternative dissemination are largely ignored. A fundamental shift needs to be considered within science, especially as places such as the European Union with the "Declaration on Research Assessment" agreement (https://sfdora.org/) are adamantly pushing for the incorporation of societal relevance and applications within scientific studies. Creation of these serious games and similar tools goes a long way in engaging an entire audience that is lost on peer-reviewed papers. The skills needed to create such games also demonstrates familiarity with, if not mastery of, skills rooted in the numerous "hard" and "soft" sciences that are involved in such a task.

5.2.2 Other dissemination methods

Similar to boundary objects, alternative dissemination methods to peer-reviewed publications need to be considered for translating scientific knowledge across sectors (such as to management) and to stakeholders. Science does itself no favors when, as far as the general society can see, the processes and results are shrouded in secrecy. Distrust in science has become a rampant issue in today's society as many messages from scientists - even those that directly relate to our own health and livelihoods - are met with skepticism, mockery and dismissal. Combatting this barrier of societal distrust means working with the general public to demystify the scientific process, as seen through, for example, citizen science initiatives. Where citizens cannot be directly integrated into the research, ensuring that messages are specifically tailored to public recipients is foundational for overcoming distrust. Peer-reviewed papers may, therefore, not be the most effective method of sharing scientific insights to the broader (or simply non-science) community. The same holds true for the management sector as paywalls to scientific papers or a lack of time to read published literature may decrease the feasibility of academia's prominent method for sharing research findings. (In relation to accessibility, all scientific research conducted in this thesis was intentionally submitted to reputable open-access journals to support the availability of knowledge.) While the survey respondents from **chapter four** indicated that peer-reviewed papers were a prominent method for interacting with scientific information, this may not hold true for managers globally or even within the same geographic regions. If academia explores other methods for sharing information aside from the established publication method, those alternative dissemination routes could be more amenable to direct management applications.

Also, like the boundary objects, there is a need to recognize the significance of information dissemination methods other than peer-reviewed papers. While not as disparate as serious games which require new skill sets, the development of dissemination documents such as management reports, policy briefings and general pamphlets takes expertise in different writing styles. Interpreting and conveying scientific messages for the consumption of people with different backgrounds, perspectives and values is key in explaining the importance of freshwater systems and spurring people into taking action. Science alone is not capable of taking strides towards the protection of vulnerable lakes, but instead needs to recognize and promote the outreach to and collaboration with other sectors and society as a whole.

5.2.3 Leveraging opportunities

Given the degree of influence that human communities and actions have on lake bodies, incorporating citizens and stakeholders alike in lake management would be beneficial in both mitigating existing challenges and preventing others from arising. Using every available opportunity for spurring on the engagement of the community in lake protection endeavors can assist in rallying support for its management. From the COVID-19 anthropause (**chapter two**), an additional outcome from the experience was the recognition that nature has been a boon for some individuals throughout the course of the distressing pandemic period, as revealed in studies describing the mental health benefits of visiting blue-green spaces (e.g. Völker et al., 2018).

Perhaps under "normal" (i.e. non- and pre-COVID-19 pandemic conditions), the role of nature in our health (physical and mental) and in our societies (socially, economically, politically and otherwise) is often overlooked because of distractions and challenges that seem more imminent and pressing to our livelihoods (e.g. Shreedhar & Mourato, 2020). For example, distractions can arise when human focus is directed away from nature due to physical separation in highly urbanized areas, work-oriented lifestyles with little personal time for hobbies, etc. Additionally, concern over environmental challenges (both looming and present) can seem more abstract, "far off" or unseen as compared to the immense amount of problems that continually arise from harmful globalization practices, societal inequalities, dire health situations, human tragedies, economic fluctuations, etc. The shifting of focus from human-nature connections to these distractions and to combating these challenges may, in part, have led to our current tumultuous relationship with nature; we are on a razor's edge with near-compromised lake ecosystems and still trying to determine how to manage the multiple and competing considerations of 1) the inherent needs of the water system, 2) the needs of human communities, 3) the widespread perception of humans as separate from nature and 4) the intensifying of numerous external pressures.

With the number of recent studies pointing towards human recognition of nature's value during the COVID-19 pandemic and anthropause, the slower pace of the world during the slew of social distancing and lockdowns may have allowed people to capitalize on chances to (re)immerse themselves in nearby ecosystems and (re)connect with nature. Regardless of the reason, there is appreciable value for these systems currently being acknowledged by many individuals and communities. Reclaiming attention towards nature can assist with prioritizing the functions and health of these systems, ultimately strengthening our society through the stabilization of our connection to nature (i.e. ecosystem services) and enhancement of our stewardship (i.e. services-to-nature). One very impactful example of this is protecting nature to avoid a future of similar, if not more frequent, global pandemic events (e.g. Rockström et al., 2021; Terraube & Fernández-Llamazares, 2020; Zabaniotou, 2020). Leveraging this nature-conscious mindset – while people readily admit the significance of these systems and have not been distracted by the "normal" hustle and bustle of life that draws them away from the biosphere – to start making permanent changes in the post-pandemic can help maintain the human-nature connection. This would offer a chance for avoiding the pre-pandemic status quo and instead introduce a paradigm shift of natural systems in the spotlight as a highly valuable but delicate part of our community's foundation.

Table 1. Research methods strengths and weaknesses

Method	Strengths	Weaknesses
Microcosm	• Treatment manipulation and replication allow for mechanistic understanding • Results can inform larger scale studies	• Environmental realism and complexity is limited
Google Search Trends	• Proxy data was available before research data	• Proxy data only informed of interest in the service, not actual use
Serious Game	• Inclusion of wide range of groups in ecosystem discussions • Approachable content for enhancing environmental literacy	• Availability or training of game moderators, if needed • Need to tailor the administering of the game for optimal multi-stakeholder collaborations
Online Survey	• Geographically wide-spread gathering of data • Small time requirement for gathering data	• Survey success depends on amount of respondents
Semi-structured Interview	• Detailed insight into management approaches for implementing the WFD	• Extensive time requirement leads to fewer interviews being conducted

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