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Towards implementation of robust monitoring technologies alongside freshwater improvement policy in Aotearoa New Zealand

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ABSTRACT

International studies point out that some freshwater policy objectives are not achieved. This study describes that this is in part caused by shortcomings that include: the lack of targeted monitoring schemes to measure impact; a too small range of specific technologies rather than a wider suite of integrated multiple technologies; a too tight focus on sub-sets of stakeholders instead of the involvement of the wider range of end users; and poor trust building and technology explanations to end users. As an example, the New Zealand government is addressing widespread concern over the deterioration of the national freshwater resource by supporting a diverse portfolio of land and riparian management actions. Efforts to assess the effectiveness of these interventions and establish an evidence-based framework for future policies are however limited by the existing regional-scale freshwater monitoring infrastructure. Such hydrometric networks were established largely to assess the broader-scale regional 'state' of the environment and are generally out-of-phase with freshwater improvement actions that are implemented more typically at edge-of-field, farm or sub-catchment scales. Recent and rapid evolution in sensor technologies have created new opportunities to deliver information tuned to the appropriate parameters and frequencies needed to evaluate improvement actions. Despite this, the necessary transformative change in freshwater monitoring has yet to gather pace. In this study we explore barriers and solutions with the objective to better understand what is needed for successful integration of innovative monitoring technologies in a transitional environmental policy setting, using recent New Zealand policy directives as a case study. We use expert surveys and scenario testing to explore barriers to adoption to more robust and comprehensive monitoring required to establish the success, or otherwise, of freshwater improvement actions. This process reveals that rather than further innovations in technology, change in the practice of environmental monitoring is limited instead by the development of defensible and accepted guidelines on the application and effective deployment of existing sensors and methods. We demonstrate that improved knowledge exchange between engineers, scientists and practitioners can be addressed and propose a new decision support and communication tool to enable the selection of monitoring technologies and solutions fit-for-purpose to evaluate freshwater improvement outcomes on multiple scales involving multiple stakeholders.

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1. Introduction

Throughout the world, robust techniques and technologies are required to monitor and prove that water quality is static, improving, or declining (Romero et al., 2016). Networks are designed, and measurements taken, to meet policy. Many governments set targets for when attributes (indicators of water quality, e.g., nutrients, water clarity, fish diversity, sediment, E.coli) must meet an objective. For example, in New Zealand, the Essential Freshwaters workplan, which builds on new policy such as the National Policy Statement for Freshwater Management (NPS-FM), aims to “start making immediate improvements so water quality improves within five years” (Ministry for the Environment, 2020). Other policy such as the European Water Framework Directive aimed to achieve “good” water quality status by 2015 (Lassaletta et al., 2010), did not and readjusted their deadline to 2027 (Carvalho et al., 2019). One of the reasons for not achieving policy objectives is not being able to detect the impact of policy changes by using a targeted monitoring scheme, i.e., a scheme avoiding lag-times by monitoring close to the action (typically implemented at edge-of-field, farm or sub-catchment scales) where the chance of detecting impact of the action is greatest (Meals et al., 2010).

Improving the design of monitoring networks to detect change has been studied since the 1940s (Zhu et al., 2019). A great deal of this work has focused on locating monitoring sites in the right place, optimizing the frequency of measurement and selecting the right range of attributes to meet water quality objectives (Strobl and Robillard, 2008). Several reviews are available that discuss this topic (e.g., Zhu et al., 2019; Jiang et al., 2020). Far less work has looked at the advantages or disadvantages of monitoring technologies and we argue that measuring attributes accurately is just as important as measuring in the right place (see, e.g., Sections 3.3 and 3.4). Of those studies that do look at monitoring techniques, most examine a specific technology such as remote sensing or networking issues (e.g., Internet of Things), rather than considering multiple technologies at once (Wang and Yang, 2019; Ighalo et al., 2021). An integrated assessment of monitoring techniques is needed.

Work to assess the suitability of techniques and technologies for use in a monitoring network has been hampered by their large range and complexity. These techniques and technologies vary according to many characteristics such as: their suitability to a waterway, cost, accuracy, and difficulty of implementation (Pellerin et al., 2016). For instance, continuous water quality monitoring to detect episodic events are cost-prohibitive and require regular maintenance for routine use and sometimes low-cost autonomous systems may suit better (Rao et al., 2013). Indeed, recent developments have seen multiple sensors deployed in low-cost arrays, coupled with wireless technologies to provide a real-time assessment of water quality on mobile devices (Alam et al., 2020). Change is inevitable as new (and better) versions replace older (and worse) candidates. However, faced with an abundance of options and characteristics, those involved in water quality monitoring (e.g. policy regulator or citizen scientist) could be paralyzed by choice when deciding what technique and technology to use in their monitoring network, or whether to abandon current (old) techniques for new techniques - especially if little information is available on their reliability.

The choice of technologies can influence the ability of a monitoring network to meet a water quality objective. For instance, depending on the attribute, sampling may have to be more frequent or continuous to establish robust outputs where attribute loads are driven by episodic events (Jordan et al., 2005; Meyer et al., 2005). This allows land owners and policy makers to account for the contribution of different land uses and land use practices to a catchment load (Harrison et al., 2019). Deriving accurate loads (or concentrations) is used to gauge the magnitude and frequency of policy interventions or voluntary actions to maintain or improve water quality (Pignata et al., 2013; McDowell et al., 2016). It is also known that when faced with accurate data and feedback, trust is built between stakeholders leading to many voluntary initiatives increasing or sustaining the number of actions for longer (Wilcock et al., 2013).

The definition of a right technique or technology may be subjective, since stakeholders may be able to access, understand and interpret technologies differently. This is exacerbated by the number of stakeholders which could include land-owners, primary industry groups, citizens, catchment groups, and regulators, but also partnerships with Indigenous groups in some countries like New Zealand (Harmsworth and Awatere, 2013). This is in line with a key warning from Behmel et al. (2016), i.e. that finding holistic solutions to cover all steps of water quality monitoring programs remains a challenge that needs to be addressed by better stakeholder involvement. To bring more objectivity into the discussion around monitoring, a decision support tool is needed, which needs to cater for different stakeholders at different scales.

Our study gathers data on the range of techniques and technologies available and combines them in a prototype decision support tool that will help stakeholders meet water quality objectives. We use the NPS-FM in New Zealand as an example as it is in an early phase of implementation and hence our analysis may prove impactful. Taking the importance of stakeholder engagement as a first priority (Behmel et al., 2016; Antunes et al., 2009; Collins et al., 2012) we first describe a stakeholder-driven process that defines the most important attributes per stakeholder group. We then use that information to build a framework that allows stakeholders to interact with a comprehensive table of monitoring technologies - seeing the advantages and disadvantages of each technology (and relevant scale). We test different approaches in three scenarios with the help of local government experts charged with implementing the NPS-FM. Based on the findings of those tests we discuss potential pathways towards implementation of these technologies into monitoring network designs for successful freshwater improvement actions.

2. Materials and methods

2.1. Prioritization of attributes

We designed a survey to explore what different groups prioritize when asked what attributes are vital for monitoring the effect of freshwater improvement actions. The survey asked respondents to choose a top three from a list of 27 attributes and asked what group they identified most with (central government, regional/local government, research organization, public, consultant, farmer/farming organization, iwi or hapū, i.e., Māori tribe or sub-tribe, respectively (used terms in the Māori language are explained in Appendix A)). The list of attributes was carefully pre-selected by the project group through a series of discussions. Details on the survey methodology and choice of attributes are in the Supplementary Material (SM, section SM 1). The survey was shared through a variety of social media and professional networks and ran from October 2020 to March 2021.

2.2. A comprehensive inventory of monitoring methods

To develop tools that could better inform a variety of stakeholders at multiple scales, we collated available monitoring technologies in a comprehensive inventory. The design of the inventory aimed at tackling the gaps mentioned in Section 1 through: providing tools for targeted monitoring schemes; providing decision support for more accurate and possibly combined technologies; an easier-to-understand overview of technologies; pairing attributes to technology better in the context of policy interventions; and better engagement with a variety of stakeholders. This work was kick-started in an initial “sand-pit” workshop with a group of approximately 15 scientists and stakeholders from industry, councils and government, including some of the authors of this paper. That workshop identified an initial set of attributes and main stakeholders and shaped the design and a preliminary version of the inventory, which was then continuously updated over the course of six months by adding technologies or additional/refined technology descriptions (approximately 50 updates). The design and updating process was coordinated by the main author and assisted by all co-authors of this paper, who provided their own expertize and learnings from previous and project-related stakeholder engagement sessions (e.g., Sections 2.3 and 2.4).

The inventory lists attributes paired with technologies to measure those attributes (Fig. 1). Each technology-attribute pair has a large amount of properties, such as cost, technology readiness, known barriers to adoption, scale, measurement frequency, precision, technology, attribute, coverage, telemetry inclusion, support needed for implementation, additional risks (such as flood damage, theft or vandalism). Initial properties were defined in the sand-pit workshop and more were discussed and added throughout the project. For example, in order to make a reasonable cost estimate, we needed to add properties of areal scale and scalability of methods, to better distinguish cost between in situ point methods and remote-sensed techniques. Another example is that multiple properties were added to better describe expertize required for use of technologies, e.g., IT expertize, expertize in translation of measurements to decision making processes and expertize in the field. SM 2 describes more detailed information on the inventory, including definition of all properties and their classification.

The inventory was developed in a hybrid approach with the intention to make both input from scientists as easy as possible, while at the same time providing an easy interface for a range of user/stakeholders, including the informed layman. The inventory was initially developed in an MS-Excel spreadsheet, to make input from a range of scientists as flexible as possible. However, given the large row and column size of the spreadsheet, we surmised that the spreadsheet would be incomprehensible for anyone other than the scientists involved in the inventory input. Hence, a more user-friendly and intuitive user interface was needed, that would also satisfy potential future web applications, e.g., web-shop interfaces. Finally, to further analyse data, there was a need to convert data to a more standardized database. Subsequently, the spreadsheet was converted to a relational SQL database. This facilitated choosing technologies per attributes in an automated workflow and enhancing interaction with the inventory in a more intuitive user interface. The interface was built in the R coding environment using R-shiny. The inventory and interface were designed so interaction could go as follows:

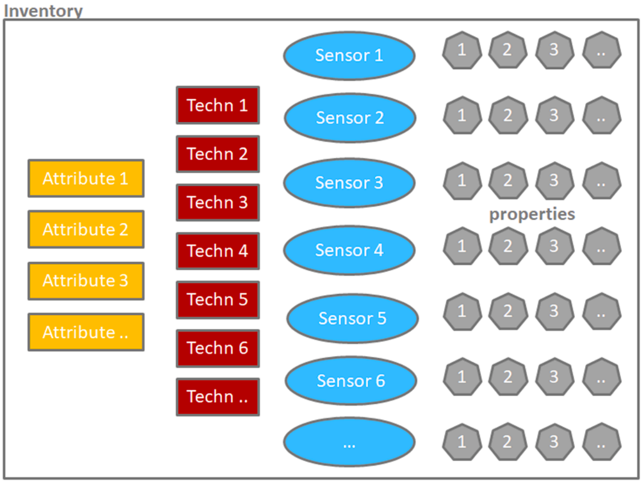

Fig. 1. Setup of the inventory of technologies. The inventory bases itself on a collection of attributes (e.g., nitrate, E. coli, water clarity), which can be measured by one or multiple technologies (e.g., UV-spectrometry, grab samples, transmissometer. For each technology, one or multiple "sensors" – note: sensor in its widest definition from perceiving something with the eye to an advanced telemetered sensor – can be available (e.g., Trios Opus, Hill Laboratory, Wetlab C-beam). Each sensor and/or technology has a wide range of properties (including cost, areal coverage, precision, technology readiness).

- a scenario contains a description of the user context, mitigation actions and subsequent attributes to be monitored "where", i.e., at what location, for example at the outflow to sea, and "when" (how often, what total time period, or at specific times, e.g., at peak flow periods);
- the SQL inventory is queried by the attributes, the monitoring requirements prescribed in the scenario and key words of the user context description;
- a list of possible monitoring technologies is exported, which include fact sheets per technology and, ideally, a "recipe for use", i.e., a text overview containing general considerations, limitations and possible disclaimers.

The inventory was developed with a draft protocol for versioning future updates (Fig. 2, bottom-left). This is mostly because: sensing and monitoring technologies are rapidly advancing; the project group who filled in first versions of the inventory do not necessarily cover all the expertize related to the knowledge of the technologies; providers of sensor technologies should be given the opportunity to add or correct, but peer-review needs to be included to warrant correct information; and input from others should be checked on completeness and errors before imported into the database.

2.3. *Exploring user interaction with three testing scenarios*

Three scenarios were tested with three different approaches (Fig. 3) to obtain more information on building a user interface applicable to a range of users (Section 2.2). Such a multi-stakeholder interface requires more than the standard set of attributes described by policy (e.g., nitrate, clarity, sediments) because it needs to include more holistic water quality attributes, e.g., Indigenous values and ecological health indicators.

The three scenarios, detailed in SM 3, described a range of realistic yet hypothetical cases, with mitigation measures, cultural importance, water body description and gave instructions for which attributes to monitor when and where. The first testing scenario described the implementation of stock exclusion and riparian planting to improve swimmability of a downstream recreation site in a small coastal catchment. The second scenario involved a range of mitigation measures to prevent deterioration of a large oligotrophic freshwater lake. The third scenario involved the exploration of mitigation measures to sustain 'mahinga kai', an important cultural indicator (e.g., Ruru and Kanz, 2020), see Appendix A) by focusing on the freshwater waterways in a small coastal catchment.

The three approaches were: .

1. gathering feedback from a "Project expert group", consisting of six freshwater monitoring experts from New Zealand research organizations;
2. gathering feedback from an "External expert group". These mostly involved regional council scientists (scenarios 1 and 2) and a Māori knowledge ('matauranga Māori', see Appendix A) expert for scenario 3;
3. automatically feeding the scenario through our comprehensive inventory.

These approaches were developed in parallel but separate from each other, i.e., each process did not know the output of the other processes until all were completed. Afterwards, the findings of the approaches were used to refine input of the inventory.

2.4. *Further interaction with stakeholders*

Approximately 25 interactive sessions (meetings, workshops, seminars and webinars) took place nationwide in between October 2020 and March 2021, informing representatives from central government

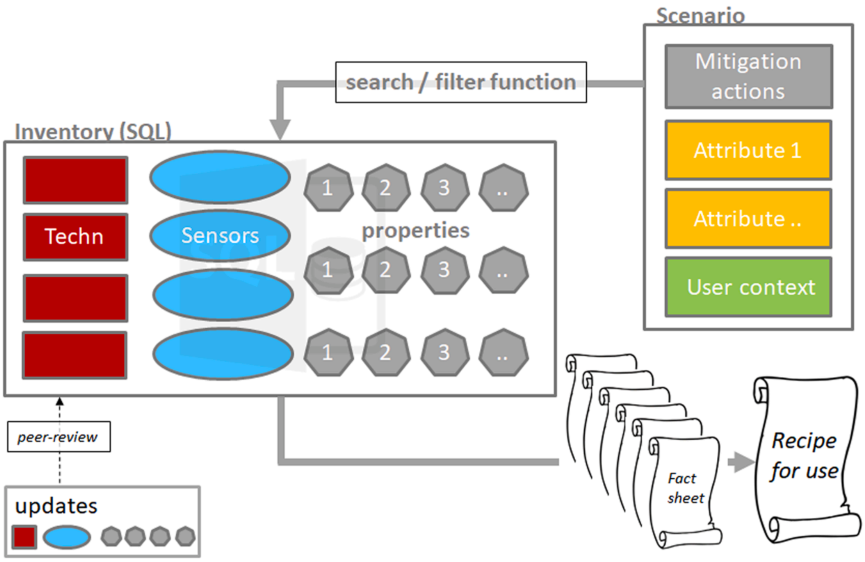

Fig. 2. The process of building an interface for interaction with the inventory as developed for testing scenarios.

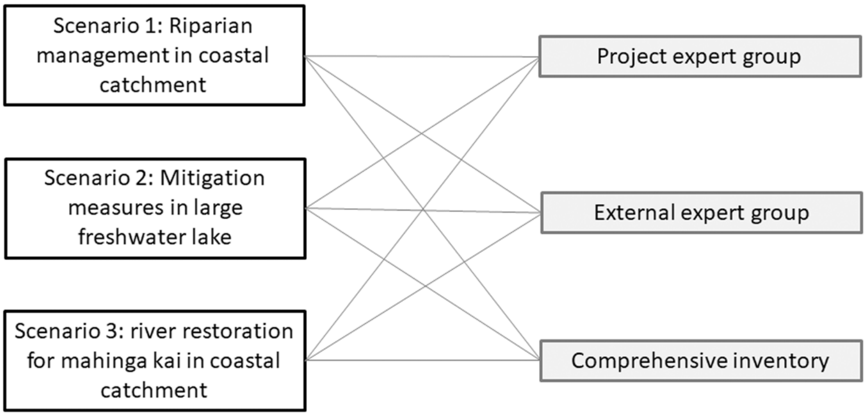

Fig. 3. Testing of different processes to obtain technologies for monitoring freshwater improvement.

departments, regional councils, iwi, river authorities, research organizations and primary industry. These sessions described the comprehensive inventory, possible ways to interact with it, and invited to play a role in testing it through scenarios. The main aims of the roadshow sessions were primarily to inform and listen, all feedback aimed as input for this study, including future improvements in the inventory and interface.

3. Results

3.1. *Prioritization of attributes: Survey results*

Our survey, designed to explore prioritization of attributes (Section 2.1), received a total number of 244 responses, which collectively prioritized nitrogen over all other attributes, followed by E.coli, macroinvertebrates, algae, and fish diversity/abundance (Fig. 4). These results are interpreted as logically following from the large attention that these attributes have received in both scientific (Monaghan et al., 2007; McDowell et al., 2013) and popular press (Radio New Zealand, 2017; Radio New Zealand, 2021a,b), being either contaminants or adversely affected environmental attributes resulting from agriculture in many parts of the low-lying coastal aquifer plains of New Zealand.

Despite the number of respondents for different groups not having a statistically robust enough sample size, it is interesting to note that different groups prioritized different attributes. For example, members of the public found algal bloom the most important, whereas iwi and hapū found the much more holistic and culturally important mauri and mahinga kai of the water (e.g., Ruru and Kanz (2020) and Appendix A) as the most important. This strengthens our earlier statements (Section 1) that different groups involved in monitoring effect of freshwater improvement have different interpretations of what freshwater improvement success looks like, including underlying freshwater values and attribute priorities. SM 1 details description of survey results.

3.2. *The comprehensive inventory*

The current version of the inventory, a collation of monitoring technologies designed to improve informing a variety of stakeholders at multiple scales, contains 47 (sub-)attributes. Each attribute has at least one, but often many technologies paired to it (e.g., manual grab samples, auto-sampler techniques, a range of in situ sensors, a range of remotely sensed technologies), resulting in 171 fact sheets of attribute-technology pairs. Each attribute-technology pair consists of 45 properties, such as cost, scale, existing standards or guidelines (all properties in SM 2). Advantages of using the relational database (SQL) approach become apparent when analysing the attributes and technologies. A quick example analysis shows that fact sheets can be analysed over their multiple properties, such as number of attributes (Fig. 5) or number of

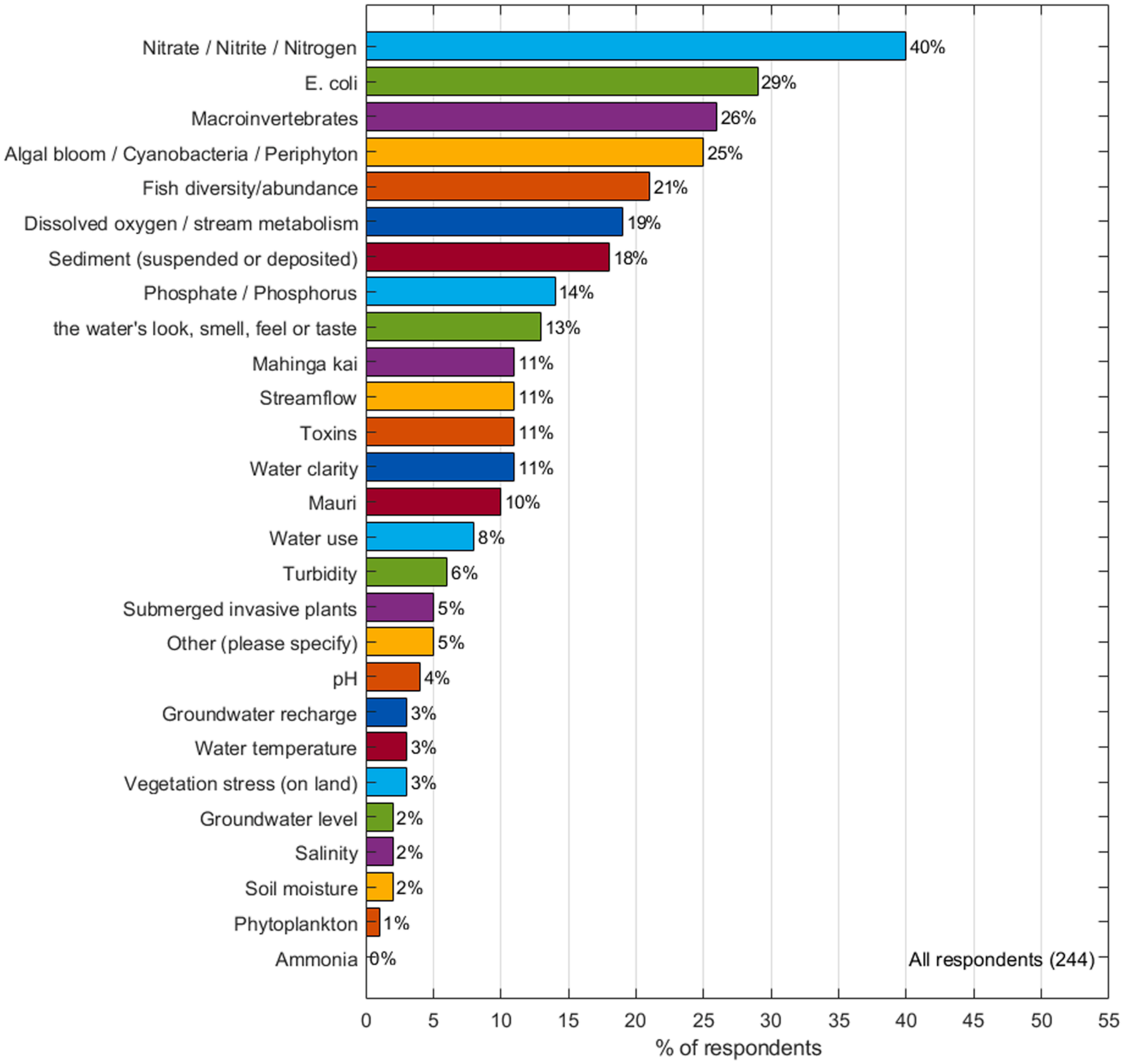

Fig. 4. Results of attribute prioritization survey: all respondents.

technologies (Fig. 6).

3.3. Results of testing in three scenarios

The combined responses from the External expert group, mostly consisting of regional council scientists, showed that regional council scientists generally have a good overview of the majority of existing technologies, both traditional manual sampling and modern (in situ and remote sensor) technologies. The combined findings of the External expert group matched the findings of the Project expert group well, with even in some cases (Table 1) the External experts outscoring the Project experts in number of proposed technologies. External experts showed a preference for the more traditional sampling approaches for monitoring, i.e. water grab samples, despite having knowledge and a keen interest in novel technologies.

The comprehensive inventory output outscored both expert groups in most cases, mainly due to the fact that a more diverse range of brands or small variations in similar methods are present in the inventory. This is no surprise, as the comprehensive inventory was built over the course of six months with many experts adding to it. Its variety is thus not so much in the number of technologies, but more in the detailing of those technologies. For example, for nutrients (Table 1), the vast amount of different nitrate sensors currently available on the market dominated the high score.

The cases where less solutions were generated by the comprehensive inventory showed the need for future improvements. For example, some smart and practical solutions were not in the inventory, e.g.: measuring E.coli in shellfish, but only when concentrations are high, or measuring Enterococci instead of E.coli in brackish environments; or practical solutions using community surveys as an input for monitoring. Another shortcoming found in the automated output of the comprehensive inventory was the lack of ability to combine, something that the experts had no trouble with. For example, the Project expert group suggested for scenario 1 that combination of methods might results in a more economically efficient set-up: "… following concurrent sampling of sediment and E.coli using one of the above methods for a period of time, a relationship between the two parameters could be investigated. If a reasonable relationship between turbidity and E.coli can be established, a reduction in sampling parameters and/or sampling frequency may be achieved". The inventory did contain input on what other methods can be used, but did not automatically identify smart combinations. Last but not least, both expert groups were able to distinguish that certain technologies were only useful in typical circumstances, e.g., fecal source tracking to find the source of contamination is only useful when E.coli concentrations are high; the automated input from the comprehensive inventory does not (yet) have that capability.

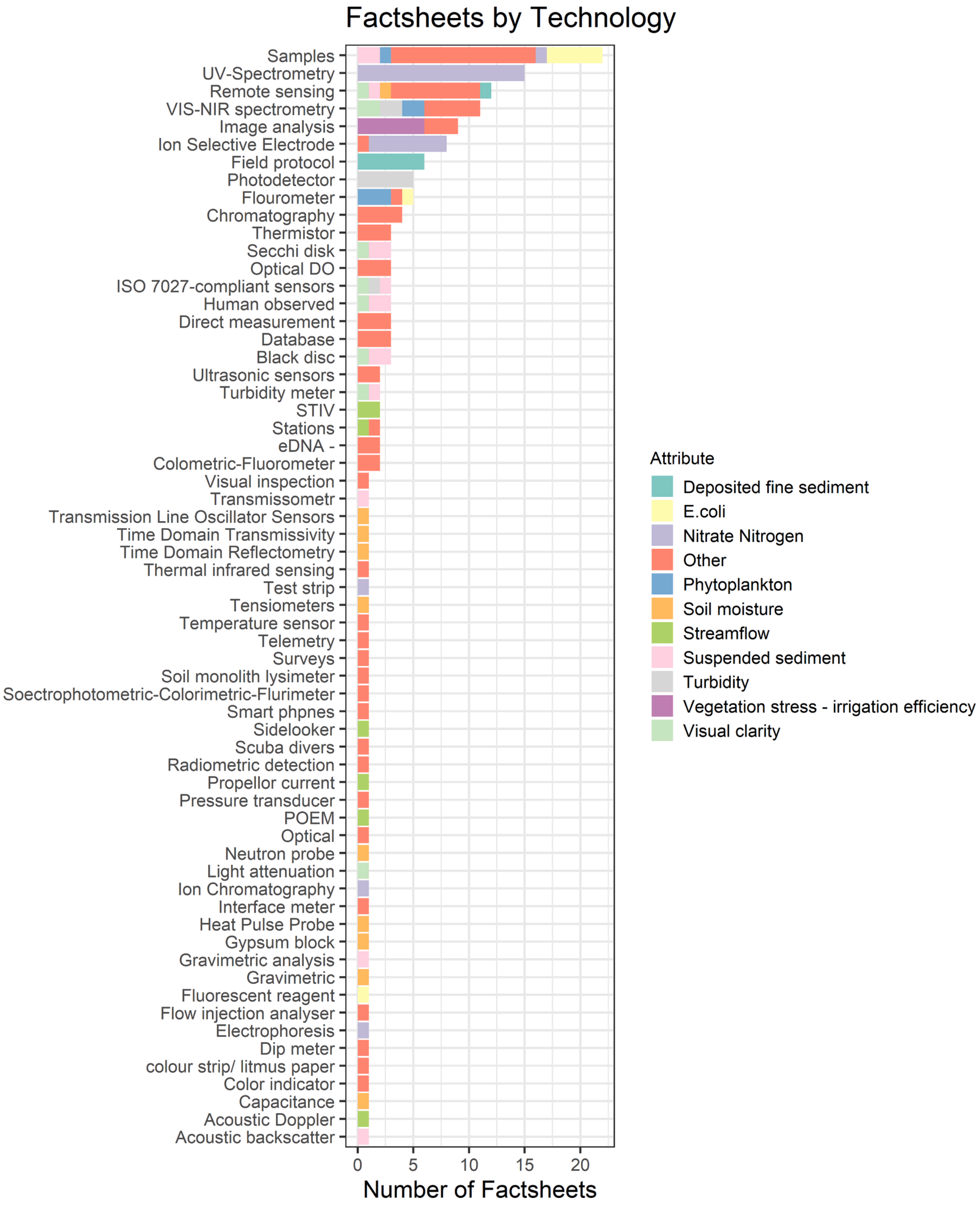

Fig. 5. Number of fact sheets associated to technologies in the inventory.

Other mentionable feedback received from regional council scientists during scenario testing was:

- that cost is an important aspects. It was often mentioned by the experts that a method would be used, because it is cheap;
- that there is no priority for lake bottom sediment, since it is not a prescribed NPS-FM attribute. However, it is an important indicator relating to land use change (e.g., Burger et al., 2008) that can be used to monitor freshwater improvement;
- that, while filling in their preferred technologies, they requested more info on types of sensors;
- a keen interest in freely available satellite data for the sake of riparian and land conversion mapping, e.g., in the Google Earth Engine (Gorelick et al., 2017).

3.4. *Findings of additional stakeholder interaction*

Conversations in the roadshow sessions focused around some discussion points relevant to this study. First and foremost, there was a strong interest in the concept of what monitoring technology would give best ‘bang for buck’ in the context of a long-term (e.g., five years or longer) monitoring approach. Choosing the best monitoring technology depends on some important factors, such as scale of the mitigation

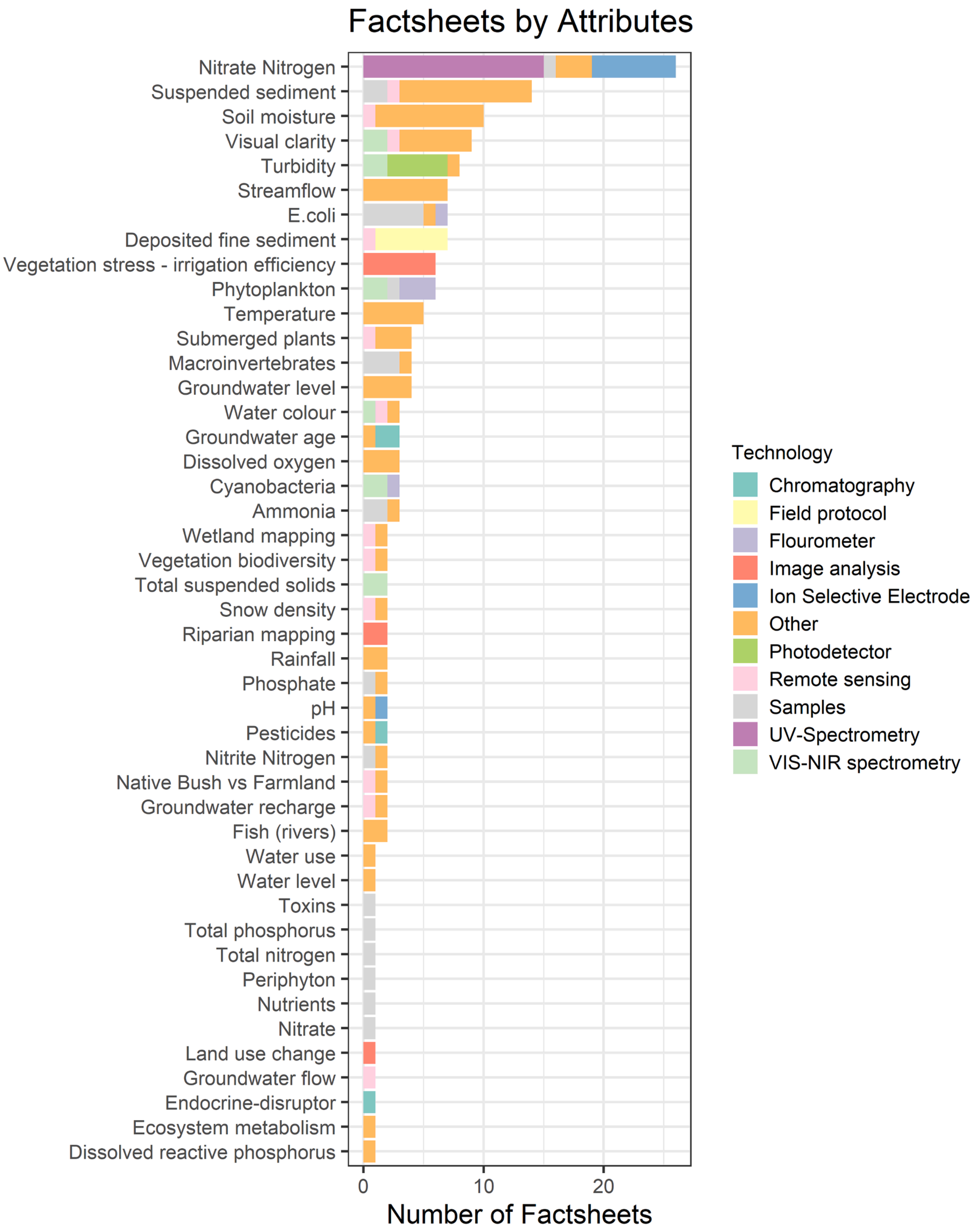

Fig. 6. Number of fact sheets associated to attributes in the inventory.

actions, scale on which the success of a mitigation action is monitored and how likely it is that change can be detected at that scale over the duration of monitoring. Hence, to optimize monitoring, the costs and measurement frequency of each technology should be used to develop cost-efficiency estimates for each monitoring technology (or combination). Alternatively, some optimization could take place by only looking at change: since freshwater improvement monitoring aims to monitor impact of an action, absolute values might therefore be less important than change and trends, opening up possibilities for methods that measure proxies over time and space, e.g., nationwide water color as an indicator for other attributes (Lehmann et al., 2018). Secondly, regional council scientists showed great interest and good knowledge in novel monitoring technologies but also indicated that they are often not deemed trustworthy enough (further discussed in Section 4.1). Last but not least, councils are interested in methods that can better involve citizens, such as from communities and catchment groups, in their science.

Table 1
Results of testing three approaches in three scenarios: the technologies proposed by each approach for each attribute.

Attribute	Project expert group	External expert group	Comprehensive inventory
E.coli	5	7	7
Suspended sediment	6	5	14
Riparian condition	4	5	4
Chlorophyll-a	2	5	10
Clarity	3	3	9
Dissolved oxygen	1	2	3
Nutrients	1	1	28
Submerged plants	2	2	4
Lake bottom sediment	1	1	1
Fish count (eel)	6	(not tested)	4

4. Discussion

4.1. Barriers to innovation in freshwater improvement monitoring technologies

The scenario testing revealed findings that are similar to other international studies, such as by Carvalho et al. (2019): the lack of info on comparability of novel methods with existing assessment methods; the need for equal scrutiny of cost-effectiveness for those methods; and lack of confidence in quality assessment of different methods. Hence, regional councils, despite being well aware of most novel technologies, would still opt for more traditional manual water grab samples. Within the current New Zealand policy framework, the barrier for regional and central government to broaden the range of environmental monitoring technologies is still high. One aspect of that barrier to adoption is cost. A council will only pay more for a technology if it has a clear advantage over cheaper methods (e.g., it has a higher temporal resolution needed to meet the council's criteria). An additional aspect is that these technologies, in order to make them ready for operational deployment, need to have ample ground-truthing, more robust method descriptions (including accuracy, scale, etc) and appropriate training in the field to gain more confidence with the technology. Another aspect is track record: even operational technologies (i.e., with a high technology-readiness level) need first to be proven in the policy framework. Substantial efforts and funding from both the technology providers as well as the trialing councils would be required to get these techniques accepted. Finally, methods can be incongruent in other ways, e.g., that: a range of novel technologies are not reporting in the required data format; have no appropriate guidelines of usage at the regional scale of the stakeholder or are through methods not yet adopted by the regional councils. Regional councils will not be able to adopt these technologies as there is too high risk that they are not defensible for long-term planning or wouldn't substantiate as evidence in Environment Court. Hence, the relative safest way for councils to monitor is through more traditional approaches. In the same way, technologies that monitor freshwater improvement well but with an attribute not prescribed in legislation (e.g., the monitoring of lake bottom sediment which is not an NPS-FM attribute) will likely not be used by regional councils.

We identified these 'low hanging fruit' (near-)operational technologies as directly benefiting from obtaining defensible guidelines: .

- Auto-sampler technologies: systems that can automatically take and store a larger amount of water samples. For example, Cassidy et al. (2018) assessed that, for total phosphorus composite loads, auto-sampler data yielded more stable data than discrete samples. The barriers to adoption are relatively low, given the relative closeness of the field analyses to lab analyses. Some remaining barriers would still require further research, such as: that some samples need to remain cool; that some samples need to be processed within a certain amount of time; and how cost-effective such an approach is for a five year monitoring campaign.
- 'lab in the field' sensors that perform analyses through a procedure in the field. Field-labs for E.coli (e.g., Cazals et al., 2020) and nutrients are already operationally available on the market. These would require an additional business case that describes cost-efficiency of monitoring over multiple years;
- A range of satellite remote sensing technologies are available at different spatial and temporal scales for attributes such as chlorophyll-a, sediment, water color (Tyler et al., 2016). Processing of remotely sensed datasets from either UAV, commercial satellites, or freely available satellite data may be able to provide options for monitoring in addition to existing tools, e.g., submerged lake plants, algal bloom, status of riparian planting actions.

In the New Zealand context, the National Environmental Monitoring Standards (NEMS, 2021) is the current vehicle for prescribing guidelines for SoE monitoring. The NEMS are a series of environmental monitoring standards, prepared on authority from the regional councils and the Ministry for the Environment, and supported by the main research organizations. As NEMS are focused around SoE, they do not describe other monitoring such as consent monitoring or monitoring effects of specific freshwater improvements. The NEMS guidelines are still largely under construction: they contain vital attributes (e.g., dissolved oxygen, soil moisture, temperature, macroinvertebrates, suspended sediment, discrete/manual sampling of nitrogen, phosphorus) but miss other important attributes (e.g., continuous nitrate, fish, pH, riparian characteristics, stream habitat, submerged plants). As the NEMS platform is widely agreed upon, it would therefore be the appropriate platform for the definition of guidelines for more novel monitoring technologies, for example those that measure the full range of attributes required for freshwater improvement monitoring as defined in this study. However, a key barrier is that in its current form the NEMS document writing only progresses slowly, largely due to those working groups being under-prioritized. Another barrier for the uptake of more modern technologies is that the costs for developing experience and guidelines into NEMS documents would lie predominantly at the regional councils, who will then need to pay for both traditional and new monitoring methods until policy changes and associated increased confidence in these technologies are developed. Extension of NEMS work toward describing guidelines – or adopting existing international guidelines or standards – for monitoring the effect of freshwater improvement would thus need a significant change of pace and funding for those working groups and associated regional council staff.

In order for governments to better align innovation with freshwater improvement, we therefore suggest to earmark some of the planned investment in freshwater improvement actions towards funds that aim towards defining monitoring guidelines for a comprehensive set of technologies, including novel tools, that are acceptable at a regional council level. Those could be in national-level actions such as: setting up observatories, including ground-truthing and training capability; improving the NEMS funding or, alternatively, fill gaps in NEMS with existing international standards, guidelines, and comprehensive descriptions, some of which already available online (e.g., Pires, 2010; Snazelle, 2020; Waters, 2018).

4.2. Have we built a helpful tool?

The attribute prioritization survey found that different sub-groups have different freshwater values, which confirms that there is a need to have a wider range of monitoring technologies available that addresses the values of different user groups, re-iterating the opportunity for innovation on monitoring technology in this research field.

The combined results from the External expert group for scenario 1 and 2 confirmed that regional council scientists generally have ample knowledge of most available technologies. However, the level of knowledge differs across councils, depending on their size and budget, with small councils often having to rely on the individual knowledge of only few people. The comprehensive inventory has the potential benefit to give more consistent advice across all councils; and the many other stakeholders mentioned in this study.

The comprehensive inventory was developed such that it can be updated (e.g., annually) with new technologies. This is particularly useful, since the project team involved in this project likely did not cover the entire range of technologies. For example, in some scenario cases the External expert Group showed a better awareness of new technologies than the Project expert group. This is another recommendation to include a greater number of councils scientists on the project team.

The automated output of our inventory generally outscored the other approaches in number of technologies, showing that there is benefit in providing a comprehensive overview of available technologies. In addition, because a relational databases was used to build the inventory, allowing unique features of statistics of properties against one another (e.g., Figs. 5 and 6), including building interfaces that allow a search for keywords and properties, e.g., searching on 'remote sensing' gives 9 possible attributes; or one can scroll through all fact sheets of a specific attribute or technology (SM 2). This paves the way to 'webshop-like' interfaces where users can search for technologies filtering on keywords, tags, different properties, etc. However, a too comprehensive output without an intelligent explanation creates the subsequent risk that people cannot choose the best method for their application. On the other hand, prioritizing one method over the other with an automated method - to create a more comprehensible shortlist - comes with the risk of being too subjective. Results of scenario testing showed that the expert groups had less trouble putting the technologies into the context of the scenario than the automated inventory approach (Section 3.3). Currently, the automated approaches only have the relatively concise Pros and Cons properties, from which a user might not be able to choose why one option is better than another. To find the balance between those two risks, we recommend focusing further developments with a fitting decision support, such as an objective weighting of some or more properties in the inventory. Reasonable first objective weighting properties are: technology readiness level; whether the technique has an existing standard or guideline; or cost.

Our comprehensive inventory and interface are intended as building blocks in the design of monitoring networks (see Section 1). Monitoring network design is considered critical to the effectiveness of policy management measures (Ausseil et al., 2021; Downes et al., 2010). As such, the stakeholder recommendation of 'best bang for buck' requires an additional inventory/interface component that should clarify the total cost for implementation of a technology over the longer term. For example, a ten year monitoring program that only uses grab samples as a technology would show an approximate linear build-up of cost (Fig. 7), which would mainly depend on the sampling frequency. The cost build-up would be more non-linear when more continuous measurements are needed and more novel technologies come into place, i.e., the initial investment of a new sensor technology is high but has a likely subsequent cheaper cost per sample. Inclusion of such additional components will likely help to make a better-informed decision on whether or not to adopt new technologies. These components are currently in the inventory but require additional details in order to develop reliable trade-offs of cost over time, e.g., cost of training differs per sensor and technology, specific maintenance costs, such as sensor fouling, the ability of sensors to robustly pick up specific shorter term events, such as floods. Section 3.4 mentioned that regional councils have a keen interest in alignment to community or citizen science technologies. So far, these have hardly been touched upon by our inventory, i.e., only one technology that contains an App for nitrate and phosphate (Rozemeijer, 2020; Costa et al., 2020). Learnings from a range of existing community driven monitoring programs, or monitoring of changes in the mauri of water through narratives common for iwi and hapū (e.g., Environment Southland, 2021), needs to be better documented in future versions of our inventory.

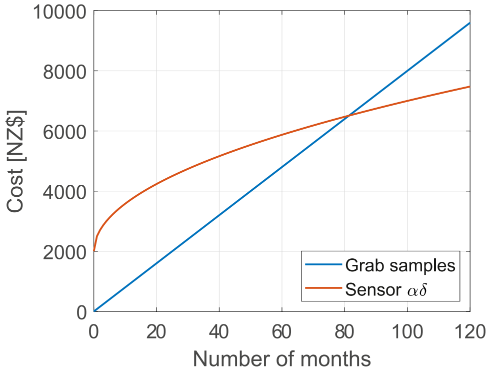

Fig. 7. Hypothetical example of a cost-efficiency curve that is recommended in future versions of the inventory. This example compares the linear cost build-up of grab samples with a novel sensor '$\alpha\delta$' that requires initial investment but becomes cheaper after 80 months of use.

The shortcomings of the comprehensive inventory approach are largely due to the automation required for developing the interface and the associated information currently in the inventory. It is recommended that any automated advice from the comprehensive inventory interface should be put into context by an expert with further scenario (beta-) testing. Further recommended technical improvements in the inventory include thorough checking for inconsistencies/typos, appropriate tags/keywords, missing attributes and exploration of any existing standards to be used for inputs (e.g., technology readiness levels, European Commission, 2020).

4.3. The New Zealand context: The key role of regional councils in freshwater improvement

Our scenario testing and stakeholder interaction led to new insights on complexity of monitoring effects of freshwater improvement actions when compared to SoE monitoring. The fairly young NPS-FM could bring unique opportunities to New Zealand for reporting on freshwater improvement, while stimulating innovation into associated monitoring technologies. However, an agreed way to monitor the success of freshwater improvement actions, at multiple scales with multiple stakeholders, has not been given enough consistent direction nor guidelines. Management actions are taking place at several scales (i.e., paddock to catchment) with the directive for these actions coming from different stakeholders (i.e., catchment groups, iwi, hapū, farmers or farming organizations, regional councils). SoE monitoring, where central government yields data from regional councils to obtain a multi-annual 'state of the environment' can hence be considered a much more top-down approach (Fig. 8, left) than freshwater improvement monitoring, requiring more complex interaction with a multitude of stakeholders. Monitoring the success of a freshwater improvement mitigation action can be considered as a type of bottom-up approach (Fig. 8, right). Regional councils are the keystone in both these top-down and bottom-up policy approaches and in most cases are connected to all of the mentioned stakeholders. This explains why this research and its recommendations are centered around the regional councils. Our decision support tool addresses the need for such a multi-stakeholder and multi-scale guidance, noting that inclusion of regional council scientists in further development will be key to address the non-trivial and significant challenge of multi-stakeholder and multi-scale guidance.

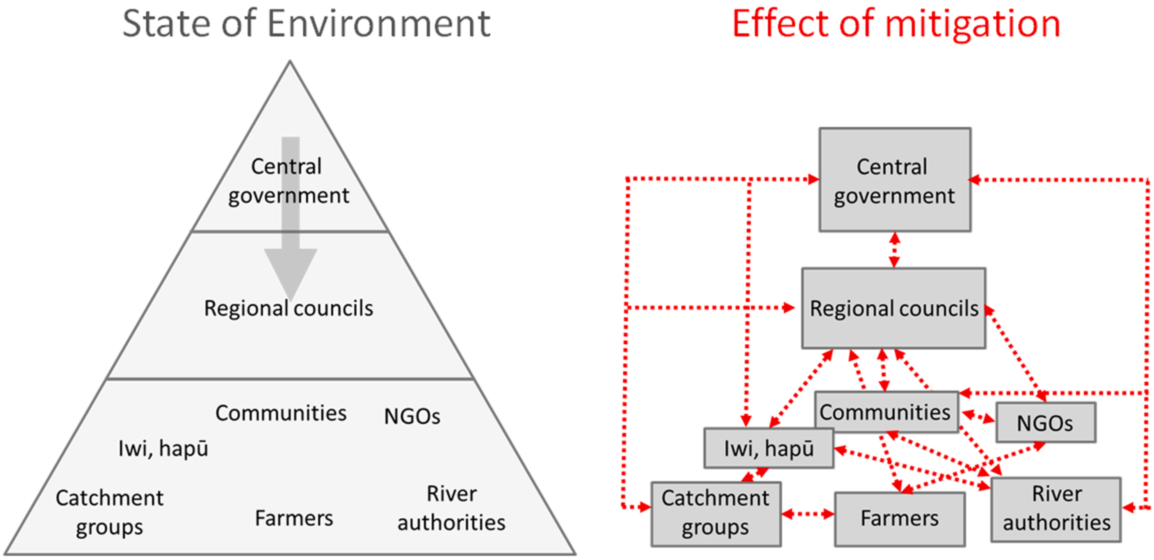

Fig. 8. Difference in State of Environment driven monitoring (more top-down) and freshwater improvement monitoring (bottom-up and sideways).

5. Conclusions

Monitoring freshwater improvement requires more targeted data than regular SoE monitoring, i.e., more frequent and at more locations. In addition, since a large variety of stakeholders are involved in freshwater improvement, different interpretations of success likely require a larger range of attributes to be monitored and thus a wider range of technologies. Our survey provided an overview on the prioritization of attributes by multiple stakeholders and signaled the different priorities of different stakeholders.

Our study developed and tested different approaches to help stakeholders identify what technologies to use for monitoring the success of freshwater improvement actions. Testing in scenarios used expert groups and a comprehensive inventory of technologies and showed that regional governments in charge of implementing environmental monitoring (in New Zealand, regional councils are the keystone in both SoE and freshwater improvement monitoring) are well aware of new technologies but would still opt for more traditional methods, e.g., manual water grab samples, even if new technologies are operational. This signals a risk that novel technologies will not be implemented for freshwater improvement legislation, which subsequently risks the long-term success of planned mitigation actions towards environmental improvement. We surmise that more urgent investment in national-level actions towards efficient deployment of novel and operational monitoring technologies, such as writing robust method guidelines (including training), will likely result in a quicker uptake of these technologies into freshwater improvement policy. This investment should include appropriate funding for those in charge of monitoring to fulfill a lead role in obtaining these guidelines.

Our proposed use of a comprehensive inventory of monitoring technologies showed that there is a potential for such tools, as they facilitate consistent information on a wide range of technologies across multiple stakeholders and could help bring technological innovation back in sync with freshwater improvement legislation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Explanation of term used in this research

- **Aotearoa**: Māori name for New Zealand;
- **E.coli**: Escherichia coli, bacteria that can be an indicator for fecal contamination;
- **Enterococci**: bacteria that can be an indicator for fecal contamination;
- **Hapū**: A division of a Māori people or community (sub-tribe);
- **Iwi**: A Māori people or community (tribe);
- **Mahinga kai**: Māori culture: “the way we gather resources, where we get them from, how we process them, and what we produce” (Ruru and Kanz, 2020). Mahinga kai is the natural connection between the atua [gods], the land, the sea, the rivers, tangata whenua and their natural resources. It is underpinned by tikanga and is rich in mātauranga Māori. Mahinga kai, as a compulsory value under the NZ National Objectives Framework, also refers to the traditions and practices associated with harvesting and gathering of species for food, tools or other resources and including the places where those species were found;
- **Mātauranga Māori**: literally means Māori knowledge and is closely aligned to the period of pre-European contact as it encompasses traditional concepts of knowledge and knowing that Māori ancestors brought with them to Aotearoa/New Zealand;
- **Mauri**: (in Māori culture) life force or essence;
- **Mokopuna**: (in Māori culture) a grandchild, or a great-nephew or great-niece;

- **NPS-FM**: National Policy Statement for Freshwater Management (Ministry for the Environment, 2020);
- **SoE**: State of Environment, The New Zealand program that drives the monitoring of the state of the New Zealand environment
- **Tangata whenua**: used to describe the Māori people of a particular locality, or as a whole as the original inhabitants of New Zealand;
- **Te Mana o Te Wai**: definition of Te Mana o te Wai (New Zealand Government, 2020) refers to the vital importance of water. When managing freshwater, it ensures the health and well-being of the water is protected and human health needs are provided for before enabling other uses of water. It expresses the special connection all New Zealanders have with freshwater. By protecting the health and well-being of we freshwater we protect the health and well-being of our people and environments. Through engagement and discussion, regional councils, communities and tangata whenua will determine how Te Mana o te Wai is applied locally in freshwater management. Te Mana o te Wai has been part of the National Policy Statement for Freshwater Management since 2014, though there are changes to how the concept is described and how it must be applied;
- **Tikanga**: customs and traditional values, especially in a Māori context;
- **Tūpuna**: (in Māori culture) a grandparent or ancestor.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.01.020.

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