Pūrongo Pānga
Rangahau Wainuku

Groundwater Research Impact Report

Science for Communities
He Pūtaiao, He Tāngata

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Ngā Ihirangi

Contents

ESR engaging with engineers, planners and environmental scientists at the NZ Land Treatment Collective (NZLTC) conference 2021.

He aha tēnei i hira ai?

Why is this work important?

In Aotearoa New Zealand, nearly half of drinking water comes from groundwater, and it is an important source for replenishing surface water like rivers, lakes, and wetlands.

Yet almost half of groundwater resources are vulnerable to contamination, and the majority that are monitored do not meet standards. Groundwater resources are also increasingly threatened by stressors like land-use change and climate change.

The groundwater team at the Institute of Environmental Science and Research (ESR) works to understand about the current state of groundwater, how groundwater will respond to stressors, and how to prevent groundwater contamination. This research is carried out through field work, laboratory analysis, and predictive modelling. ESR's groundwater research focus is broad: from developing novel technology to trace groundwater contamination, to mapping the impact of on-site wastewater management systems on groundwater, to studying chemical and biological factors that signal the presence of nitrogen in groundwater.

Our groundwater researchers work closely with ESR's wider water and environment team to build knowledge of groundwater, understand and mitigate contamination sources, and to protect groundwater for future generations. Collaborating with partners from other CRIs, iwi, regional and district councils, and the water industry is also vital to inform equitable groundwater management and policy.

Our changing climate makes this research even more important. From droughts to intense rainfall, New Zealand is experiencing an increased frequency of extreme weather events, resulting in rapidly fluctuating groundwater levels. This increases the potential for groundwater to mix with contaminants from agricultural systems, sewage, or sea water, among other sources. Microbial transport to groundwater also increases in saturated conditions, putting human health at risk of more waterborne disease. ESR's research strives to understand both the current threats to groundwater management and to predict what future challenges we might face, to ensure we can keep working to safeguard groundwater resources.

As project leader Dr Louise Weaver says:

"Instead of a 'flush and forget' mentality, ESR is helping to shine a light on the unseen world of groundwater, so that our communities and environment are protected and treasured as a taonga."

Groundwater is water that is stored underground in space between rocks or sediment particles. Rain and surface water seeps through the soil to get into these underground spaces, called aquifers.

A Mātauranga Māori understanding of groundwater is that it is the amniotic fluid of the earth mother, Papatūānuku. This amniotic fluid is nourishing and provides for life on earth, so keeping groundwater healthy keeps the people healthy.

Te tiaki i ō tātou waimāori i te tahumaero mā te hangarau hou e whakamahi tauira whaihanga ana

Protecting our freshwaters from waterborne diseases using novel surrogate technology

Contaminated freshwater can harbour many waterborne pathogens (protozoa, bacteria, viruses), which can cause gastroenteritis and other diseases in humans. By mimicking the physicochemical properties of important waterborne pathogens, abiotic pathogen surrogates (non-living biomolecule-modified synthetic particles) can be used to predict water contamination risks in freshwaters, and help to design improved water treatment systems and water-supply bore protections to keep our drinking water safe.

Dr Liping Pang, a Science Leader at ESR, has led several multidisciplinary research projects that bring together national and international experts in biotechnology, applied microbiology and contaminant water engineering to develop pathogen surrogate techniques.

The problem

Globally waterborne pathogens kill 1.8 million people and cause about 4 billion cases of illness annually, and New Zealand is not immune to this risk. For example, contamination of water-supply bores in 2016 in Havelock North caused 8320 cases of illness.

To keep drinking water safe for human consumption, water-supply must be free of waterborne pathogens that are often present in contaminated surface-water and groundwater. This is where the use of pathogen surrogates comes in as an investigation tool to tackle the problems.

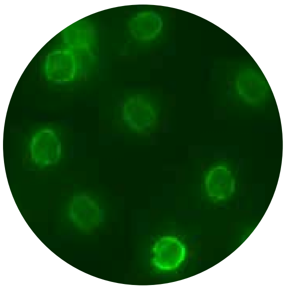
The solution

Abiotic surrogates are non-living synthetic particles coated with coated with biomolecules such as vitamins, proteins or amino acids. They can be used to investigate pathogen removal and transport in freshwater environments, and to assess the performance of water and wastewater treatment systems.

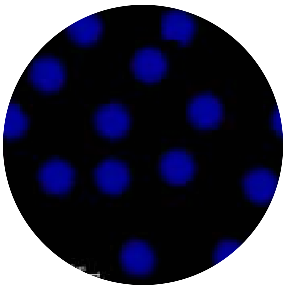
The surrogates can be labelled with unique synthetic DNA tracers that the same research group have developed. Surrogates' DNA degradation can mimic pathogen inactivation to some degree. DNA-tagged surrogates can be analysed sensitively and rapidly using the quantitative polymerase chain reaction (qPCR). DNA tracer labelling also allows effective tracking of the surrogates from multiple contaminant source locations and pathways (see article about the synthetic DNA tracers).

The transport and reduction of pathogens in water systems are largely determined by their size, shape, buoyant density, surface-charge and hydrophobicity (how attracted to or repelled by water they are on page 8).

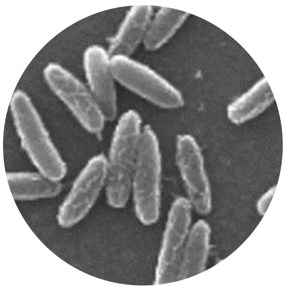
Fig. 1. / *Images of pathogens and surrogates.*



Cryptosporidium parvum oocysts diameter 4.86 (± 0.24) µm

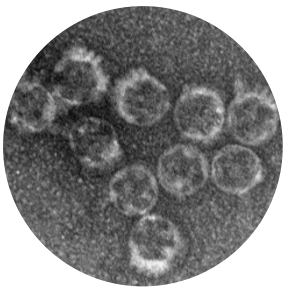


Cryptosporidium surrogate microparticles diameter 4.92 (± 0.04) µm

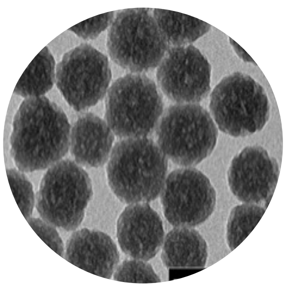


Legionella pneumphilia
1.43 (± 0.34) µm long
0.32 (± 0.03) µm wide

Legionella surrogate microparticles
1.25 (± 0.18) µm long
0.97 (± 0.22 µm wide



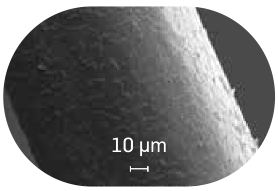
Rotavirus
diameter 78 (± 9) nm



Rotavirus surrogate nanoparticles
diameter 75 (± 11) nm

Human hair
diameter 50 µm

(Credit: CC 3.0 Nicola Angeli/MUSE)



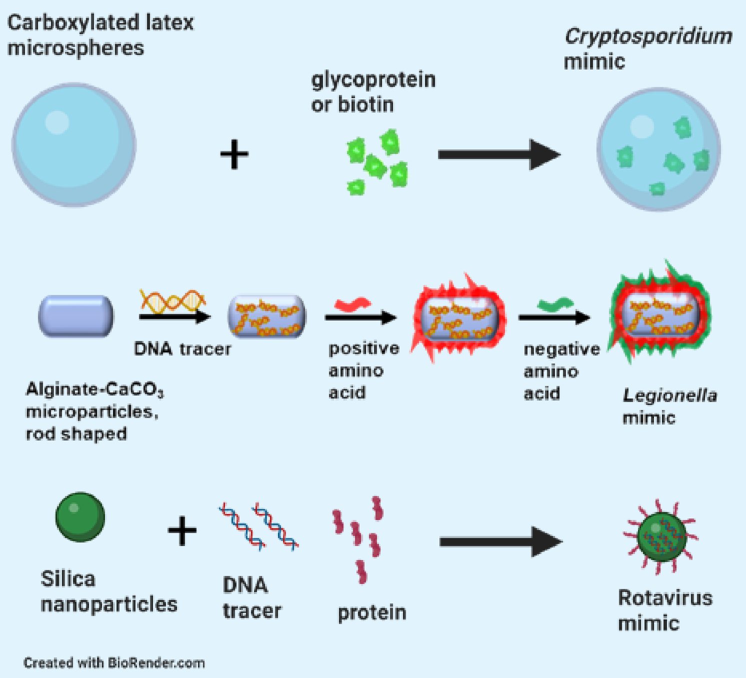
Targeted waterborne pathogens

New Zealand has a higher incidence of drinking-waterborne cryptosporidiosis than other developed countries due to high livestock densities. Cryptosporidiosis is caused by the protozoa *Cryptosporidium parvum/ hominis*, which are shed in the faeces of infected humans and animals. These parasites are hard to kill by conventional disinfection. This means that stopping water contamination in the first place is the best strategy to prevent disease.

Likewise, the bacterium *Legionella pneumophilia*, which lives in freshwater and engineering water systems (e.g., cooling towers, premise plumbing, hot water tanks, etc.), causes a particularly nasty form of pneumonia called Legionnaires' disease. There is no vaccine, and its mortality rate for hospitalised patients is 5–30%. The annual incidence of legionellosis cases in New Zealand is approximately 5.4 per 100,000 people, but legionellosis is often under-diagnosed.

Rotavirus is another leading cause of gastroenteritis, particularly in children. It is among the most infective pathogens, just one viable rotavirus particle may cause infection. Therefore, rotavirus is used as a model virus for microbial risk assessment for drinking and recreational water, as well as for determining the safe setback distances between water-supply bores and on-site wastewater disposal.

Fig. 2. / *Surrogate diagram.*



How surrogates are made

- The *Cryptosporidium* surrogates are carboxylated latex microspheres coated with glycoprotein (the major type of protein that *Cryptosporidium* oocysts produce on their cell walls but is also found in many safe sources such as biotin (vitamin B7).
- The *Legionella* surrogates are rod-shaped, DNA-encapsulated, amino acid-modified alginate-calcium carbonate microparticles.
- The rotavirus surrogates are DNA-labelled, protein-coated silica nanoparticles.

Liping's teams have created surrogates that mimic these properties of the nano-sized rotavirus, micro-sized *Legionella* bacteria and slightly larger *Cryptosporidium* protozoa.

These pathogens and surrogates are small! Compared to the diameter of human hair, the diameter of *Cryptosporidium* is 1/10th (10%), *Legionella* 1/36th (2.8%) and rotavirus is 1/667th (0.15%) (Fig. 1).

Experiments conducted in New Zealand and overseas have validated these new surrogates' performance against the actual pathogens:

- Filtration of *Cryptosporidium* and surrogates in alluvial sand and limestone sand, and their reduction in a pilot plant with coagulation and rapid sand filtration;
- Reduction and transport of rotavirus and surrogates in coastal sand aquifer media, in stony alluvial soils under on-site wastewater applications, and their adsorption to unmodified and hydrophobically modified quartz sand;
- Attachment of *Legionella* and surrogates to biofilms grown on stainless-steel material in flow-through bioreactors that simulated plumbing conditions, in the presence and absence of residual chlorine.

These research findings demonstrate that these new surrogates significantly outperform existing surrogates, like unmodified microspheres for *Cryptosporidium* oocysts and MS2 bacteriophage for viruses (see examples in Fig. 3).

In a pilot study conducted at the Invercargill water treatment plant, the *Cryptosporidium* surrogates were used to evaluate the effectiveness of filter materials used in New Zealand treatment plants for protozoan removal, including anthracite coal, pumice sand, and engineered ceramic sand (ceramic sand performed best). These new surrogates have also illustrated that turbidity (cloudiness), a key test of water clarity and existing proxy for water quality, may not be a reliable indicator of protozoan removal.

ESR researchers also evaluated different types of domestic water filters for *Cryptosporidium* removal, including activated carbon, silver-impregnated carbon, pleated paper, polypropylene and polyester cartridges that had pore sizes 1-2 μm. Although both carbon filters outperformed all the others, only the 1 μm activated carbon filters removed the protozoan surrogates to the Australian/New Zealand Standard.

Future perspectives

Now the race is on to expand these surrogates' usage and to advance surrogate technology.

In collaboration with Professor Elmar Prenner's group in the University of Calgary, the current research team

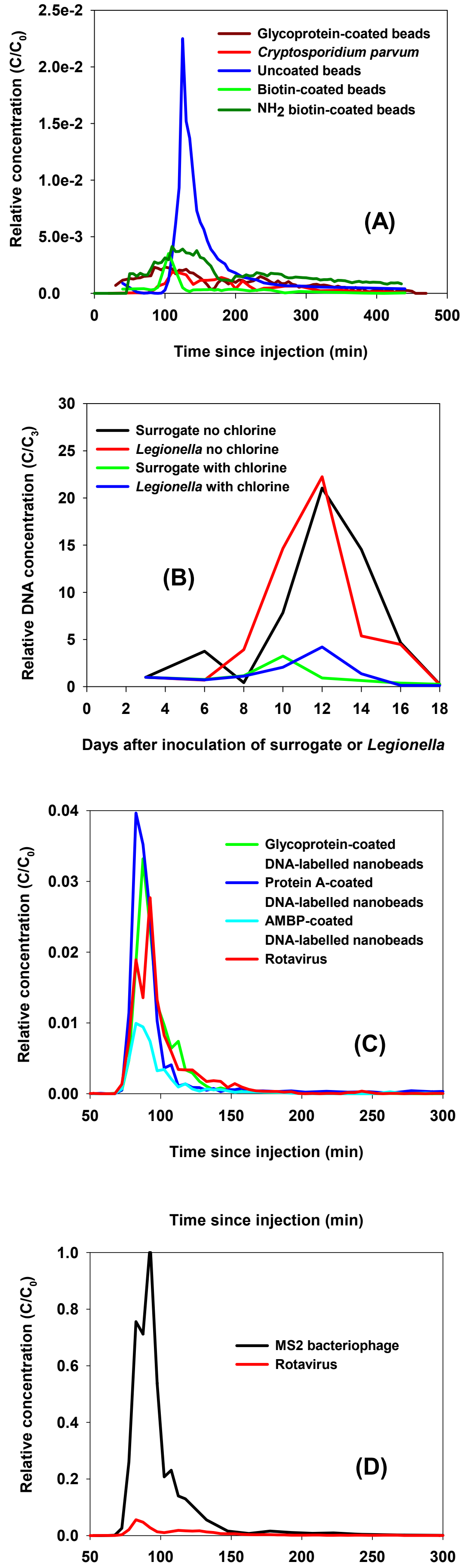


Fig. 3. / *Examples (right) of surrogate mimicking reduction and transport of pathogens in water systems.*

(A) Cryptosporidium *and surrogate filtration in alluvial sand,*

(B) Legionella pneumphilia *and surrogate attachment to biofilm-grown stainless-steel material in flow-through bioreactors,*

(C) and (D) rotavirus and surrogate transport in coastal sand aquifer media.

(Liping Pang, Craig Billington, Sujani Ariyadasa, Beth Robson, Aruni Premaratne, Richard Sutton, Susan Lin, Panan Sitthirit) are working on creating and validating a new generation of surrogates made from food-grade biocompatible and biodegradable natural biopolymers, expanding their applications across real-world operational water systems.

Proof-of-concept studies suggest that the new pathogen surrogates show great promise as new tools for water applications. The surrogate technology approach has opened a new avenue for assessing pathogen removal and transport in water systems without the risk and expense that accompany work with actual pathogens. The research findings will facilitate improved management systems and engineering approaches to reduce waterborne infection risks and safeguard public health in Aotearoa New Zealand and around the world.

Funding support

[1] Royal Society of New Zealand

- Marsden Fund ESR-1001: Micro-mimics: Mimicking virus removal and transport in groundwater using surface charge-modified, DNA-labelled silica nanobeads
- Marsden Fund ESR1601: A new approach to studying *Legionella* mobility and persistence in engineered water systems

[2] The Health Research Council of New Zealand

- HRC Fund 16/206: Community water supplies: ensuring microbial safety for disease prevention
- HRC Fund 22-586: Preventing Legionellosis: New Technology to Test Engineered Water Systems

[3] ESR's Strategic Science Investment Fund (SSIF): funded by Ministry of Business, Innovation and Employment (MBIE)

- Novel pathogen surrogates – Developing novel food-grade pathogen surrogates for water quality applications
- Additional support from the Invercargill City Council

Lake Wairarapa.

Te whakahou i te whaiwhai wai: ngā kaiwhaiwhai pītau ira hou

Revolutionising water contamination tracking using new synthetic DNA tracers

ESR researchers have developed DNA tracers that can track sources and pathways of water contamination. The tracers consist of 20 different DNA sequences, each with a unique identifier, that can be used to generate precise location details to help with effective contaminant management.

Dr Liping Pang, a Science Leader at ESR, has led an MBIE Smart Ideas Project "Tracking water contamination using smart DNA tracers" to develop synthetic DNA tracer techniques.

The problem

Aotearoa New Zealand's freshwater resources have been significantly polluted due to the intensification of human activities. Nitrate concentrations are higher than natural levels at 39% of groundwater monitoring sites, and 5% of these sites have nitrate concentrations exceeding safe drinking-water guidelines. Microbial pathogens in freshwater sources also pose a major health risk. The lack of accurate location information for freshwater contaminant sources and pathways hinders effective freshwater contaminant management.

The solution

To address this urgent need, Liping and her team have developed new DNA tracers that can track sources

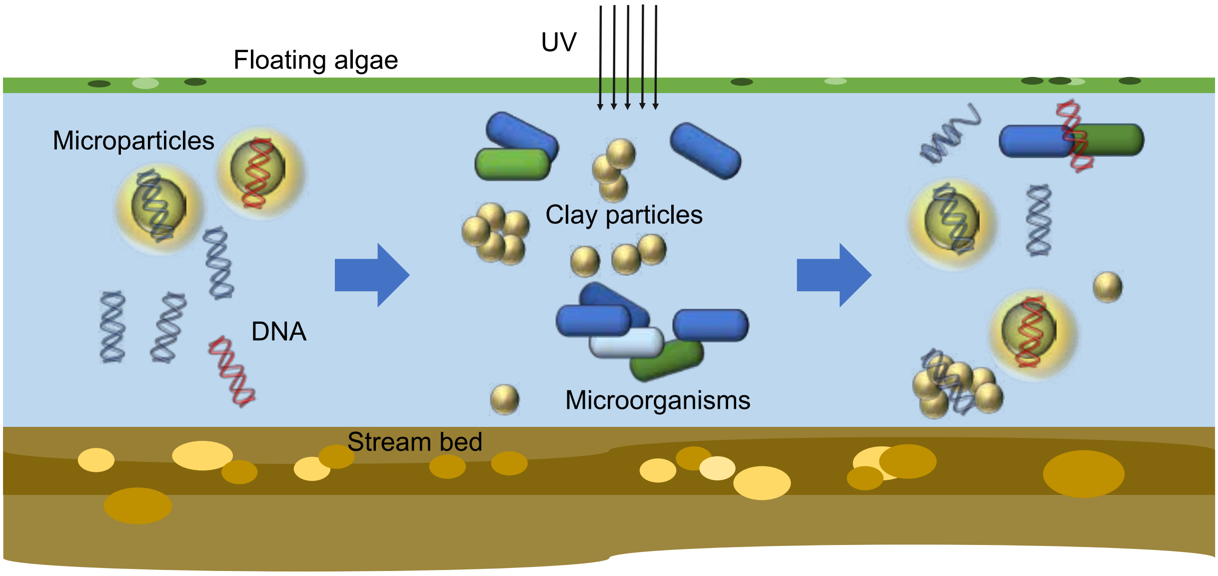


Fig. 4. / *Transport of the free and microencapsulated DNA tracers in a surface water stream.*

and pathways of water contamination. They have developed 20 different DNA tracer sequences, each with a unique identifier, available as either free molecules or encapsulated within food-grade biopolymer microparticles.

The free DNA tracers can diffuse into the porous media of soils and aquifers, whereas the microencapsulated DNA tracers are protected from the environmental stresses (e.g. ultraviolet radiation, microbial activity, enzymes and chemicals) that are often encountered in surface water (Fig. 4) and effluent.

These new DNA tracers are biocompatible, biodegradable and nontoxic, so they can be used in ecologically sensitive freshwater environments.

In collaboration with Environment Canterbury and Waikato Regional Council, ESR researchers have validated the use of these DNA tracers by tracking them through surface water, groundwater and soil systems.

They found that the DNA tracers were directly detectable in groundwater and soils, and could be tracked in a surface stream for at least one kilometre.

Compared with the free DNA tracers, the microencapsulated DNA tracers displayed significantly less degradation in surface water and wastewater (Fig. 6), demonstrating their suitability for use in these environments. The free DNA tracers are more suitable for use in aquifers and soils because they are removed to a lesser extent by filtration.

ESR researchers measured the degradation of these DNA tracers in stream water, groundwater, and domestic and dairy-shed effluent, and their adsorption to stream sediments, soils, coastal sand aquifer media and alluvial sandy gravel aquifer media. The DNA tracer degradation rates were established for a range of environmental conditions. These data could be used to inform the design of future field investigations.

Synthetic DNA refers to artificially made DNA molecules that are designed using computer software and created through chemical synthesis in the lab. The process of DNA synthesis involves specialised machines (Fig. 5) that chemically assemble individual DNA bases into specific long sequences. Unlike naturally occurring DNA, synthetic DNA is not derived from a living organism and doesn't code for any genes. Synthetic DNA can be engineered to include specific sequences that are not found in natural DNA, which makes it a powerful tool for research and technology.

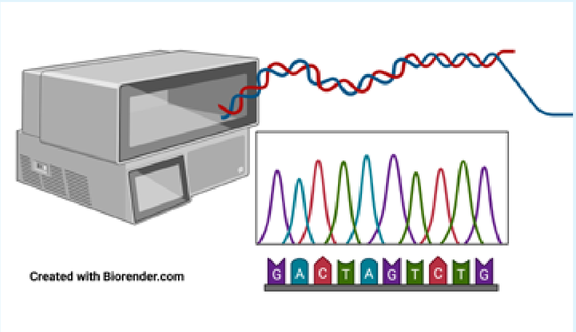


Fig. 5. / DNA tracer synthesis.

This new class of microencapsulated DNA tracers has been developed by ESR from biocompatible, biodegradable, and nontoxic naturally occurring biopolymers.

The microparticles comprise DNA-loaded chitosan cores and alginate shells (Fig. 4), which are extracted from crustaceans' exoskeletons and brown seaweed, respectively.

The positively charged chitosan cores bind to the negatively charged synthetic DNA tracers, and the alginate shells effectively protect the DNA from environmental stresses and degradation.

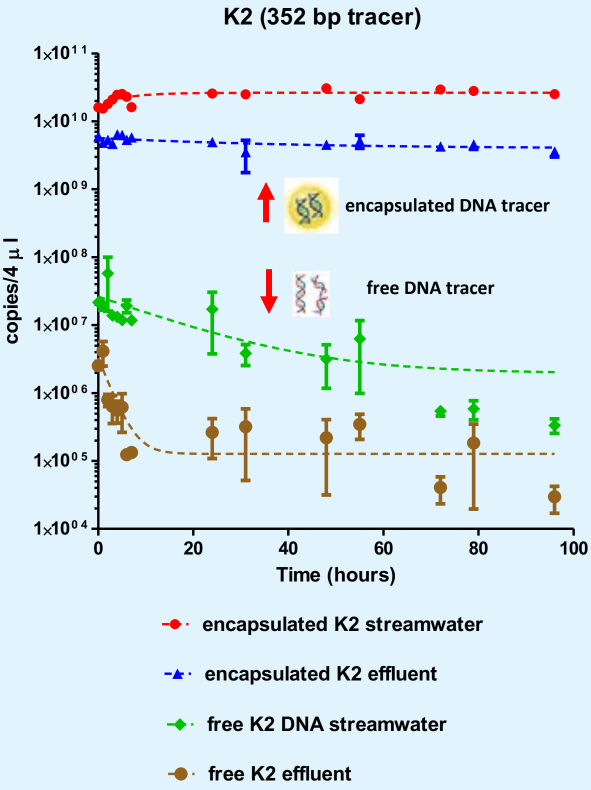
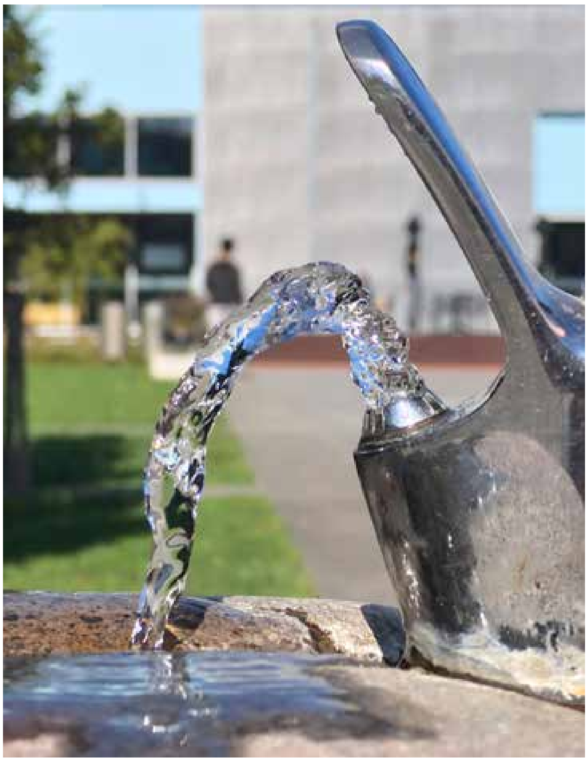


Fig. 6. / *Degradation of free and microencapsulated DNA tracer in stream-water and dairy-shed effluent.*

Funded through MBIE Smart Ideas Project. Additional support from Environment Canterbury and Waikato Regional Council.



ESR researchers have evaluated a portable qPCR device, Liberty16 in collaboration with Ubiquitome Ltd, and a portable DNA detector, OptiQ in collaboration with the University of Calgary, as well as a continuous low-level aquatic monitoring (CLAM) device. The preliminary validation results suggest that it is possible that DNA tracers can be monitored and analysed in the field.

DNA tracers have been also used to label pathogen surrogates that the same research group have developed to facilitate their sensitive detection by using the quantitative polymerase chain reaction (qPCR). DNA-labelled surrogates not only can act like DNA tracers but also mimic pathogen reduction and transport in freshwater (see article about the synthetic pathogen surrogates).

The DNA tracer technology addresses a key capability gap in investigating contaminant flow paths spatially (in space) and temporally (in time). DNA tracer technology could help local authorities and environmental engineers simultaneously track multiple pollution sources and pathways in freshwater environments. By providing accurate spatial information, it will drive mitigation actions that will protect and improve New Zealand's freshwater resources.

This DNA tracer technology also has broader applications, for example product authentication, protecting high-value goods, and in forensic, hospital and ecological investigations.

ESR Senior Scientist Bronwyn Humphries samples an OWMS.

Ko ngā rangahau e ārahitia ana e ESR kei te tūhura i ngā pūnaha whakahaere waipara i te wāhi mahi, ā, me te pānga i runga i te kounga o te wainuku

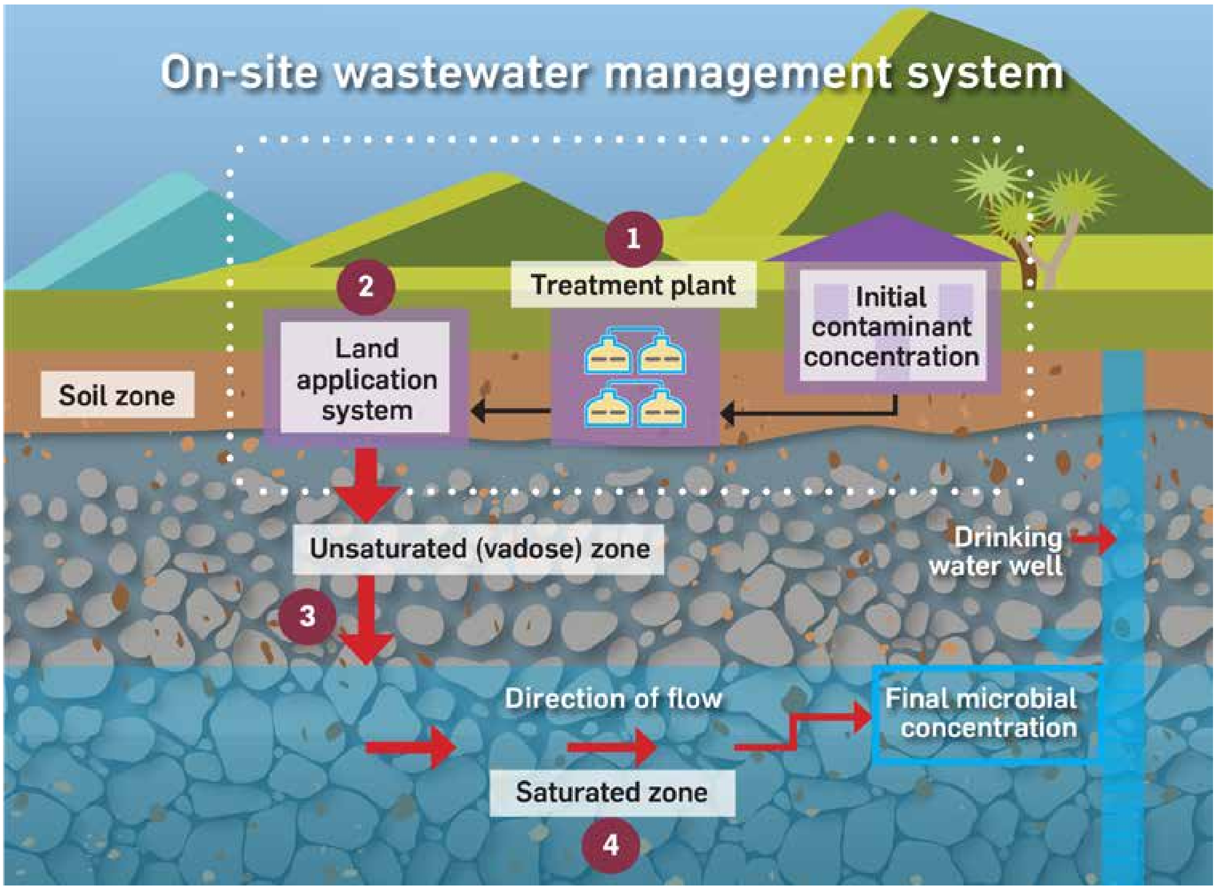
Research led by ESR investigates on-site wastewater management system performance and their impact on groundwater quality

Up to 20% of households in parts of Aotearoa New Zealand are reliant on on-site wastewater management systems. These systems can affect groundwater and the drinking water system that relies upon it.

ESR Senior Scientist Dr Bronwyn Humphries and a team of microbiologists and environmental scientists work to understand how on-site wastewater systems impact groundwater.

The problem

Outside of reticulated wastewater areas, Aotearoa New Zealand relies on on-site wastewater management systems (OWMS), many of which were installed before 2000, when resource consents were not required. While regional councils have information about consented OWMS since 2000, records for systems installed prior to this date often lack information about their location, type and/or condition. Anecdotal evidence suggests that systems are not adequately operated and maintained with wastewater removal companies reporting many failed systems around the country. Management of these systems presents a challenge



for both owners and regulatory bodies, and the risks from contamination can affect both environmental and human health.

In 2018, ESR led sampling of over 120 shallow wells around the country, and emerging organic contaminants (EOCs) were found in 70% of these sites (Fig. 8). In fact, caffeine and sucralose EOCs were found *upstream* from centralised wastewater systems, suggesting that on-site wastewater systems are the ones contributing these EOCs to groundwater.

Understanding how these on-site systems perform is important because of the downstream impacts on groundwater, which is where 40% of drinking water in Aotearoa New Zealand comes from. Bronwyn is leading a research team to understand how these systems perform, with a specific focus on removal of microorganisms and viruses that cause human disease, and chemical contaminants such as nitrate.

The solution

Working with Environment Canterbury, Waimakariri Regional Council, ecoEng Ltd, Whiterock Consulting Ltd and with a system supplied by Hynds Wastewater. The team is working at a domestic OWMS field research facility in rural Canterbury to investigate the impact of the system on groundwater quality. The research team has installed in-situ sampling points into the on-site system and 13 sampling wells located around and

Fig. 7. / *This diagram shows the opportunities for microbial and chemical removal in an on-site wastewater management system and the receiving environment: 1) the OWMS treatment plant, 2) land application system, 3) vadose zone (unsaturated zone) and 4) saturated zone.*

i

Emerging Organic Contaminants (EOCs) are like molecular 'fingerprints' of human activity. They are molecules that don't occur in the environment naturally, so their presence can point to a source of contamination. Some of them are new contaminants recently introduced to products or medicines. Other EOCs may have been present as a contaminant for decades, but only recently detected or considered to be of concern. Their impact on human, animal, and environmental health – as well as their presence in various environments – remains poorly understood. EOCs include preservatives, birth control hormones, caffeine, pharmaceuticals like paracetamol, plasticisers and many, many more.

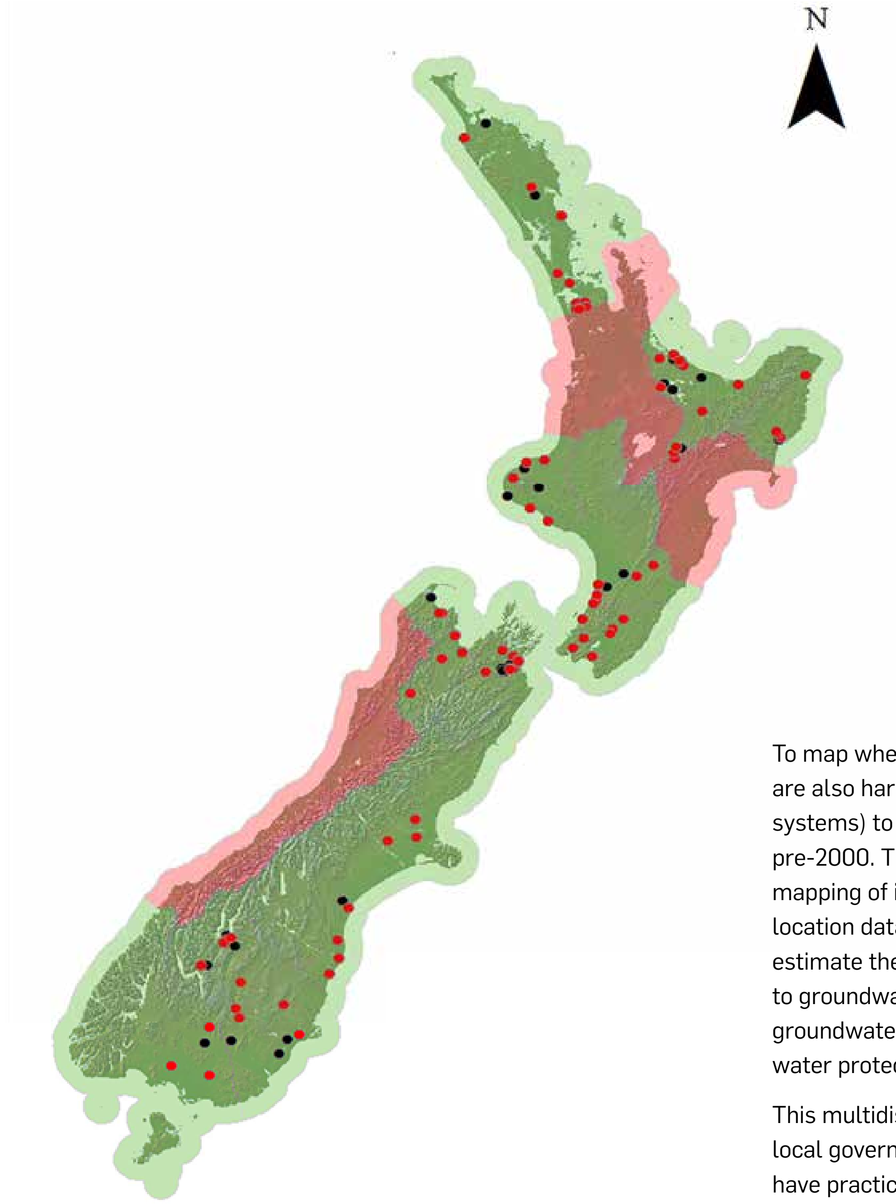
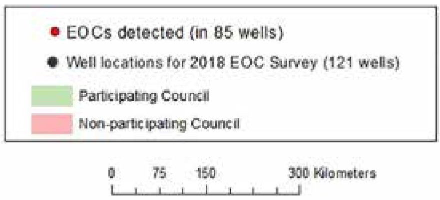


Fig. 8. / *Map showing the sampling well locations (121), highlighting where EOCs were detected (85 – in red dots). Areas excluded from survey also shown (red areas).*



downstream of the wastewater land application system (LAS) – the 'land disposal field' of the OWMS.

Testing this system involves 'dosing' it with non-pathogenic versions of *E.coli* bacteria and viral indicator organisms, as well as chemical markers, and measuring how these tracers move through the LAS and into groundwater downstream. Preliminary results indicate that while bacteria were filtered out by the LAS, the viral and chemical tracers were detected two metres downgradient in the groundwater within two hours.

The research team is now investigating the contribution of on-site systems to nitrogen in groundwater, as well as the fate and transport of pathogen surrogates used as tracers. In addition to monitoring this field-scale OWMS, the team is sampling up to 30 on-site wastewater systems in Canterbury of varying designs. These samples will be analysed for chemistry, microbiology, emerging organic contaminants and anti-microbial resistance, adding to the knowledge of effluent composition sourced from OWMS's.

To map where these OWMS are located, ESR scientists are also harnessing AI and GIS (geographic information systems) to locate and count the OWMS installed pre-2000. This work allows fine-resolution location mapping of individual OWMS – and knowing accurate location data, when combined with models that estimate the chemical and microbiological contribution to groundwater from these systems, will inform groundwater policy and enable improved drinking water protection planning.

This multidisciplinary approach across researchers, local government, design engineers and industry will have practical applications in managing OWMS, their impact on groundwater, and decisions about protecting our drinking water systems.

Supporting material

Learn more about Bronwyn's and ESR's work in understanding OWMS performance, location and impact on groundwater on ESR's website.

Funding support

This work is funded by MBIE, supporting research to optimise wastewater treatment in Aotearoa New Zealand to reduce risk to public health. Additional support from Environment Canterbury, Hynds, Whiterock Consultancy and ecoEng Ltd.

Reference Paper:

Close, M. E., Humphries, B., & Northcott, G. (2021). Outcomes of the first combined national survey of pesticides and emerging organic contaminants (EOCs) in groundwater in New Zealand *2018. The Science of the total environment, 754*, 142005. https://doi.org/10.1016/j.scitotenv.2020.142005

www.sciencedirect.com/science/article/pii/S0048969720355340?casa_token=0feu-8P05o8AAAAA:XRwx2daGdsEZEkCcHTf6kPa4XllQlOSU4JObY1xUx0l79_4Tzj5GkDX6kZoaUUJD4OHoIRTtPyk

He huarahi tikanga-maha ki te whaiwhai i ngā mātāpuna parahanga i te wainuku, mā te whakamahi i ngā aruaru matū, moroiti hoki

A multidisciplinary approach to tracking pollution sources in groundwater using chemical and microbial tracers

Emerging organic contaminants (EOCs) and environmental DNA (eDNA) are innovative tools that can be used to identify sources of pollution in groundwater. Using these tools, a team of ESR scientists is analysing the presence of EOCs and the diversity of species through eDNA, to build a predictive model for pollution source identification and aid targeted mitigation.

Dr Andy Pearson, Dr Louise Weaver and a team of chemists, microbiologists and environmental scientists at ESR research pollution source modelling, and impacts of nitrate pollution on groundwater quality, and offer solutions to help manage it.

The problem

Groundwater provides us with baseline flow for our rivers and streams, 40% of Aotearoa New Zealand's drinking water, irrigation of agriculture and horticulture, and is of high cultural and recreational importance. Nitrate is a major pollutant of groundwater in Aotearoa New Zealand.

Although there are natural processes that produce nitrate as a part of the nitrogen cycle, human activity is unbalancing this cycle, which means nitrate ends up in our waterways and groundwater. The main source of nitrate that leaches into groundwater is from fertilisers used in agriculture, but other sources of nitrate pollution include leaking sewage pipes, on-site wastewater management systems, landfills, and municipal wastewater systems. This makes it challenging to differentiate pollution sources and manage them effectively in catchments with multiple potential sources.

Determining a better measure of the source of contaminants in groundwater can enable a targeted response in mitigating the risk.

In Aotearoa New Zealand, emerging organic contaminants (EOCs) have been recently detected in groundwater, and their presence can be used to track pollution sources. EOCs act like a chemical fingerprint and have been previously used in tracking a range of pollution sources (such as wastewater treatment plants and septic tanks) in other countries. ESR scientists are using the same methods to differentiate sources of contamination in Aotearoa New Zealand.

Environmental DNA (eDNA) analysis provides insights into the biological diversity of various environments. While its use has primarily focused on larger species, eDNA analysis is now being extended to smaller, single-celled organisms. The combination of EOC analysis and eDNA analysis can help in the identification of specific sources of pollution and inform effective management strategies to protect groundwater quality.

The solution

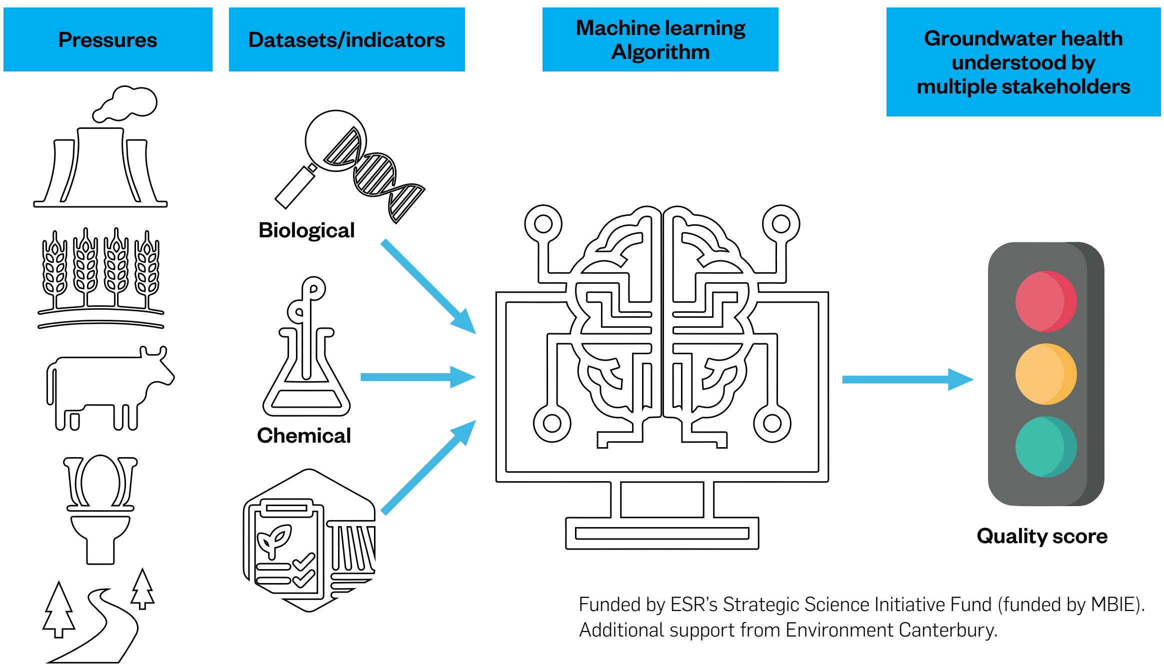
The primary goal of this project is to use EOCs and eDNA to identify and delineate pollution sources. To achieve this, the ESR team will analyse groundwater that is close to different types of pollution sources and measure the presence of EOCs and eDNA at the point of discharge, such as from on-site wastewater management system (OWMS) outflows.

ESR researchers will develop a predictive model for identifying specific contaminant sources using eDNA targeted at micro to macro-scale organisms, combined with the presence of key contaminants including EOCs. This model will help effective management and regulation of pollution by allowing regional councils to detect sources of contamination, especially in catchments with multiple potential sources.

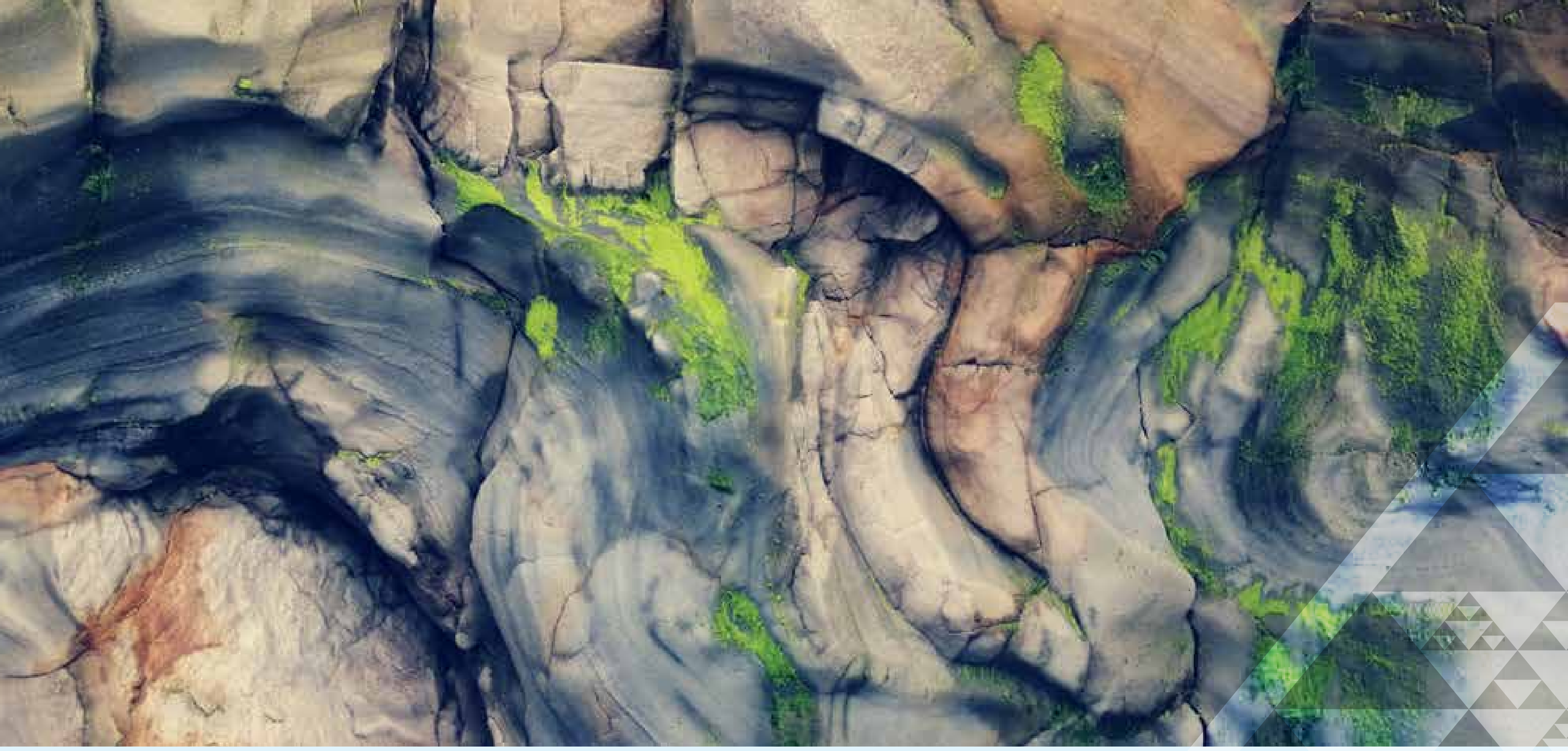
Environmental DNA (eDNA) refers to the genetic material shed by organisms into their environment, like water or soil. This genetic material can be extracted from environmental samples and analysed to identify the presence of different species without direct observation. eDNA analysis has become increasingly popular in recent years for its potential applications in biodiversity assessments, ecological monitoring, and invasive species detection.

The process of eDNA analysis typically involves collecting environmental samples such as water, soil or sediment, filtering and extracting the DNA from the sample, and sequencing the DNA to identify the species present. This can provide a non-invasive method of detecting species in a particular place, especially for species that are difficult to detect through traditional survey methods. eDNA analysis has been used in a variety of settings, from monitoring fish populations in rivers and lakes, to detecting rare or endangered species in remote environments. However, like any technology, there are limitations and challenges associated with eDNA analysis, including issues of sensitivity, specificity, and interpretation of results.

Fig. 9. / A diagram showing how information from different sources is fed into the machine learning algorithm which then creates groundwater health metrics.



Funded by ESR's Strategic Science Initiative Fund (funded by MBIE). Additional support from Environment Canterbury.



Te tūhura i ngā pūnaha wai huna: te mana o ngā tauira wainuku e mārama ai, e whakahaere ai hoki i ō tātou manawa whenua

Uncovering the hidden water systems: the power of groundwater modelling in understanding and managing our aquifers

Groundwater is an important source of drinking water in Aotearoa New Zealand but it is expensive and difficult to collect samples and data. Complex models are paired with cutting edge statistical and mathematical tools and techniques are used to understand groundwater systems, but they must be tailored to the specific environment and questions being asked.

ESR Science Leader Dr Theo Sarris and a team of hydrologists, modellers and data scientists, work on these complex models to help manage groundwater: studying contamination risks, mitigation options for reducing nutrient levels, management of groundwater resources and integration of AI tools into groundwater hydrology.

The problem

Although groundwater connects to our surface water systems and is a major source of drinking water for Aotearoa New Zealand, it is unseen and often difficult to access. Sampling groundwater – drilling wells the surface, through the water-table and hundreds of meters below – is a costly and slow process. Researching groundwater systems through sophisticated models can leverage these expensive 'data points' of groundwater sampling and incorporate the vast gaps with statistical descriptions. For these models to be useful in understanding and managing our groundwater, they must be specific to the environment and to the questions being asked.

The solution

Dr Theo Sarris and the ESR team develop highly complex models to simulate aquifer structures and how these affect the movement of contaminants and pathogens (Fig. 10). The goal is to provide insights and predictions that would be difficult or impossible to obtain through observation alone. They can help us understand the behaviour of water and contaminants in the subsurface, informing resource management decisions and risk assessments.

In one example, Theo and the team investigated diffuse agricultural nitrate leaching and nitrate removal within a catchment basin with only limited knowledge of the complexity of chemical heterogeneity – the variation in the complex chemical composition of soil due to differences in the mineral content, organic matter, and pH levels across different locations. The model used a hybrid catchment-scale flow and transport model paired with a Machine Learning model to evaluate the effectiveness of targeted area regulation. The study showed that when land use decisions are science based, outcomes (in this case better surface and groundwater quality without minimising economic activity) will always be improved. If management zones are delineated based on chemical heterogeneity and groundwater flow paths, land use regulation in discharge-sensitive zones was twice as efficient compared to other management options.

These models are an important tool for understanding complex groundwater systems and making informed decisions, but they should always be used with caution and with an awareness of their limitations.

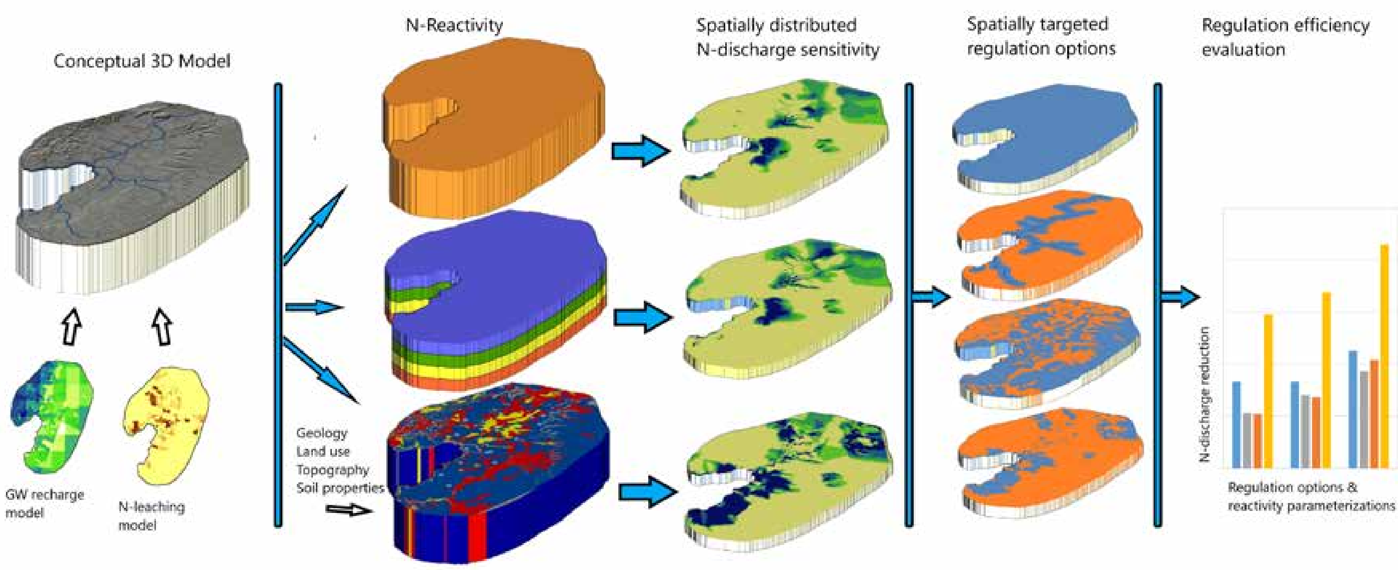
Monte Carlo is a statistical method used to estimate an uncertain outcome by simulating many equally possible scenarios. It is commonly used in various fields, including finance, engineering, physics and computer science.

The method involves generating a large number of random samples, each with its own set of parameters or inputs, based on a prior knowledge. These samples are then used to simulate the outcome of a system or model. By running the simulation many times, the Monte Carlo method can provide estimates of the likelihood and range of potential outcomes for a given scenario, along with associated levels of uncertainty.

Monte Carlo simulations can help to assess the risks and potential impacts of complex systems or models, by allowing researchers or practitioners to identify the most critical parameters or inputs and evaluate different scenarios. The method is often used in conjunction with sensitivity analysis, which helps to identify which parameters or inputs have the most significant impact on the outcome of the simulation.

As Monte Carlo analysis involves a large number of simulations, it is a computer-intensive process and can take considerable time and computational effort to conduct.

Fig. 10. / *Steps and key elements for the modelling for assessment of targeted regulation efficiency*



Funded by ESR's Strategic Science Initiative Fund (SSIF), funded by MBIE. Additional support from He Wai Māpuna and in collaboration with Ngā Hapū o Te Matakana me Rangiwaea and Te Rūnanga o Ngāi te Rangi.

Tasman District Council Resource Scientist Joseph Thomas and ESR Science Leader Louise Weaver sample groundwater, Golden Bay.

Te mārama ki te ora o te wainuku: te pūnaha hauropi huna e tautoko ana i tō tātou wai matahīapo

Understanding groundwater health: the unseen ecosystem supporting our precious water

By understanding the role of key organisms in aquifer ecosystems, researchers are developing a groundwater health index to help mange and protect this taonga.

Science Leader Louise Weaver works with a team from ESR and Auckland University that combines data scientists with experts in hydrology, microbiology, and modelling, to develop a practical tool for predicting groundwater health from chemical and biological indices.

The problem

Groundwater is a vital taonga that supplies 80% of water into Aotearoa New Zealand's rivers and streams and 40% of our drinking water. The perception is that groundwater is a sterile environment, but in reality, underground microbes support a complex ecosystem that keeps the groundwater clean and healthy by processing contaminants such as nitrates. However, these natural underground communities of organisms are under threat due to the volume and cumulative effects of contaminants coming from land use, not to mention increasing climate stress affecting the whole water cycle. There is still much to learn about groundwater organisms and their functions in removing contaminants and the emerging stressors on their ecosystem.

The solution

Researchers from ESR and Auckland University are studying the organisms that exist in underground aquifers to understand their roles and responses to contaminants, and developing an index that indicates the groundwater ecosystem's health (Fig. 11). The scientists are also building a picture of the stresses the groundwater environment is under, and by tracking the changes in biological diversity, they can monitor water quality.

Dr Louise Weaver says changes in above-ground ecosystems are well understood because they have been studied intensively for so long. "Take for example the African Plains – we know what the lions and zebras do and how they interact. By comparison some of the macroinvertebrates and microorganisms in groundwater systems have yet to be identified, let alone understanding their interactions." Louise says one of the challenges has been identifying the organisms that play a part in removing nitrates in groundwater.

Now, the team is refining sampling methodologies using specialised techniques. For example, larger macroinvertebrates can be captured using nets (Fig. 12.), while smaller organisms require pumping large volumes of water from the ground, filtering, and extracting eDNA (environmental DNA) to identify what is present in an aquifer (Fig. 13.). Researchers are creating a useable database to help understand regional differences in groundwater systems and detect new organisms, from microbes through to macrofauna living in groundwater.

Aside from the inherent conservation value in the array of organisms present in groundwater, this research could also lead to bio-remediation techniques. By understanding the ecosystem processes and organisms involved, in the future it may be possible to introduce some of these organisms into the aquifer to enhance bio-remediation processes and improve groundwater quality.

This new *Groundwater Health Index* is aiming to become a practicable tool for predicting the health of groundwater and monitoring the stresses and changes to this vital yet hidden ecosystem.

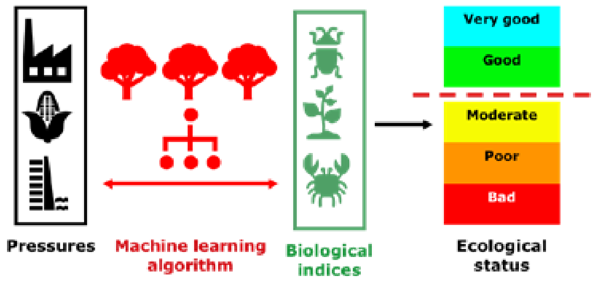
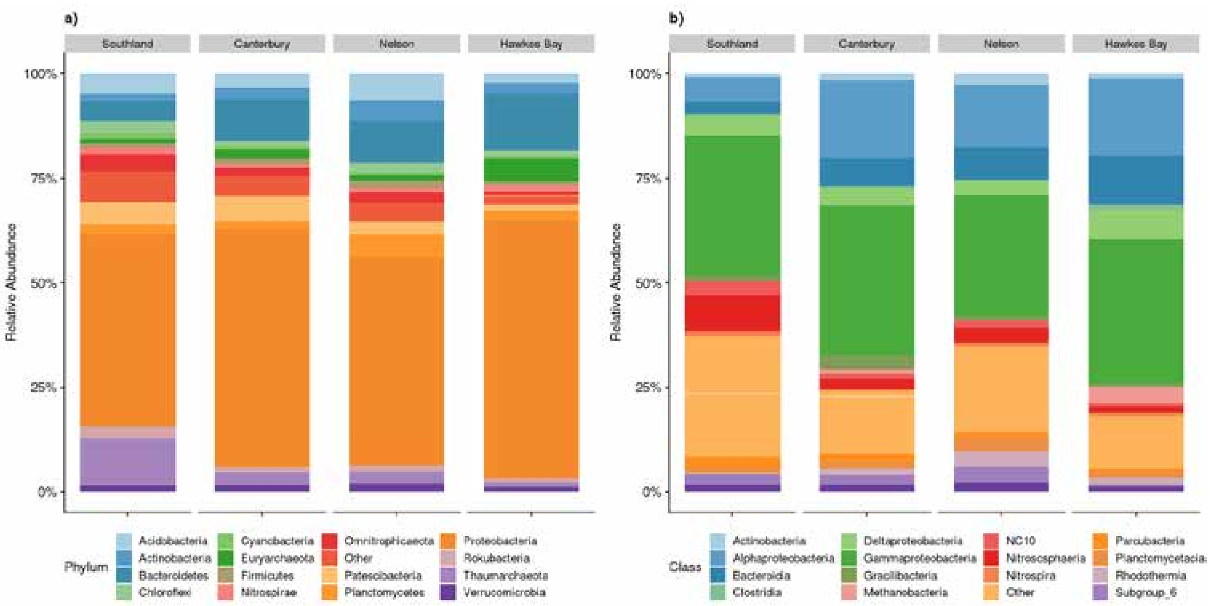


Fig. 11. / *Predictive tool development. We are combining data from eDNA, water chemistry, taxonomic identifications, geological settings and using predictive models to identify sentinel species present and predict their response to anthropogenic and climate change scenarios.*

Fig. 12. / *A groundwater amphipod. Photo credit: Annette Bolton.*

Fig. 13. / *Below regional median abundance of bacteria present in eDNA samples: a) Phylum level, b) Class level of diversity.*



Funded through ESR's Strategic Science Initiative Fund (SSIF), funded by MBIE. Additional support from Tasman District Council, Otago Regional Council, Environment Southland, and Hawke's Bay Regional Council.

Denitrification wall under construction.

Te whakawātea i te wai: ngā tikanga auaha o te tango i te pākawa ota i te wainuku

Clearing the waters: innovative techniques for removing nitrate from groundwater

Woodchip can help reduce nitrate in water systems, through building woodchip bioreactors and through installation of woodchip permeable 'walls' buried into groundwater. These two nitrate mitigation practices have been studied in Aotearoa New Zealand, and they have different applications and designs which must be carefully considered.

Principal Scientist Murray Close, Science Leader Theo Sarris, Senior Scientist Andy Pearson and a large team from ESR (Louise Weaver, Phil Abraham, Laura Banasiak and others) and DairyNZ (Lee Burbery) are monitoring the installation and long-term performance of denitrification systems.

The problem

Nitrate leaching, particularly from agricultural land use, can cause water contamination, and traditional mitigation practices may not be effective in all landscapes. Nitrate is a highly mobile contaminant that can easily travel from the surface to groundwater. As nitrate discharge can have adverse effects on both environmental and human health, it is crucial to implement effective measures to mitigate its impact.

The solution

ESR researchers studied the results from a woodchip bioreactor trial in an open drain in South Canterbury, and from a woodchip denitrification wall trial in a shallow alluvial, fast-flowing gravel aquifer on the Canterbury Plains (Fig. 14).

The bioreactor was effective at reducing nitrate, but it also had the potential to initially export dissolved organic carbon to the farm drain, which could be an environmental hazard. Careful planning and monitoring

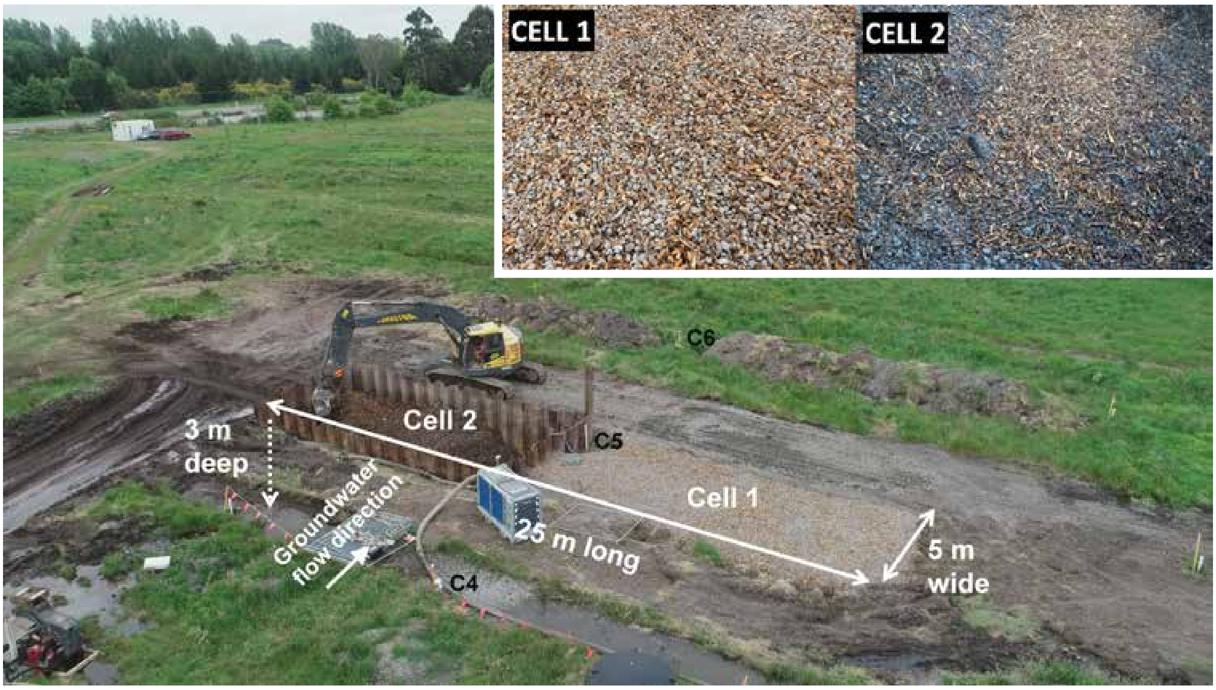


Fig. 14. / *Pictures of the 50/50 woodchip/gravel mixtures that make up the denitrification wall, and a showing installation works. Cell 1: chipped wood mixed with 20-40mm gravel rounds. Cell 2 hogged wood mixed with parent aquifier material, screened of material under 20mm diameter. The positions of monitoring wells C4:C6 are marked on the photo.*

are both required to mitigate this issue at the start of the operation.

Despite the woodchip wall initially leaching dissolved organic carbon, it was also effective at nitrate reduction. The nitrate removal rate of the woodchip wall was higher than previously predicted, and while it slightly increased the emission of methane gas, the emission of nitrous oxide was less than for pasture.

Both woodchip bioreactors and denitrification walls can be effective nitrate-mitigation practices, but they require careful design and monitoring for their specific applications. The woodchip bioreactor was effective in reducing nitrate in an open drain, while the woodchip denitrification wall was effective in a heterogeneous, fast-flowing gravel aquifer. Further long-term studies are needed to evaluate their effectiveness and potential environmental impacts.

Woodchip denitrification

Woodchip is a carbon-rich material that supports the growth of microorganisms that transform nitrate in water into nitrogen gas, a process known as denitrification. When water containing nitrate flows through a bed of woodchip, microorganisms use the carbon in the woodchip as an energy source and reduce the nitrate to nitrogen gas through a series of biochemical reactions. The nitrogen gas is then released into the atmosphere, effectively removing it from the water.

The process of denitrification requires a specific set of environmental conditions, including the presence of carbon, the absence of oxygen, and an appropriate temperature range. In a woodchip bed, the carbon is provided by the woodchip itself, and the absence of oxygen is achieved by controlling the flow of water through the bed.

Woodchip bioreactors offer an effective and sustainable way to remove nitrate from agricultural runoff and other sources of contaminated water. However, proper design and management are important to ensure their effectiveness and to avoid potential environmental risks, such as the release of dissolved organic carbon into the water.

Funded through ESR's Strategic Science Initiative Fund (SSIF), funded by MBIE. Additional support from Dairy NZ.

Te tautiaki i te wai inu i Aotearoa: te taputapu Aromatawai Whakamōrearea Morioiti mō ngā mahi whakamahi whenua

Protecting drinking water in Aotearoa New Zealand: the Microbial Risk Assessment tool for land use activities

Protecting our drinking water from potential microbial contamination is critical for regional councils. An effective approach to assessing the risks posed by land use activities in close proximity to protected drinking water zones is needed to assist councils in making informed consent decisions.

Principal Scientist Murray Close and Science Leader Dr Theo Sarris works with a team from ESR (Allanah Kenny, Bronwyn Humphries, and Meg Devane), GNS (Catherine Moore, Brioch Hemmings, and Conny Tschritter) and Environment Canterbury (Lisa Scott) on a new model for microbial risk assessment of land use on drinking water supplies.

The problem

Regional councils in Aotearoa New Zealand need a robust method to assist in making decisions about land use activities near water supply wells that could potentially impact the safety of the drinking water. Some land use activities within designated drinking water protection zones may require resource consent, and risk modelling can aid in determining whether consent is required and should be granted. The need for a defensible method for assessing a wide range of land use activities prompted the development of new tool to model microbial risk to drinking water supply wells.

The solution

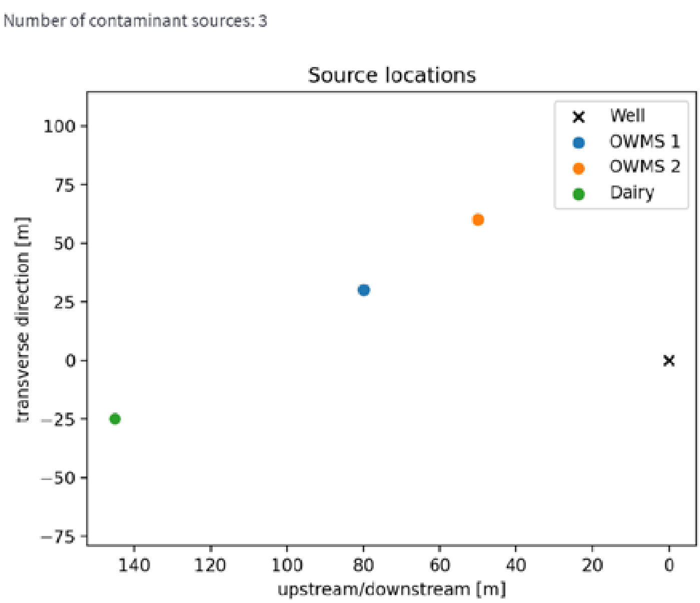
Working with a range of groundwater modellers, hydrologists and microbiologists, Murray and the teams at ESR and GNS, along with the Environment Canterbury (ECan), developed the Microbial Risk Assessment (MRA) tool to provide a more objective and transparent basis for consent decision-making on land use applications (Fig. 15). This risk assessment tool involves modelling potential microbial contamination of groundwater supplies from land use activities such as community and on-site wastewater management systems, pastoral farming, wildfowl, stormwater systems, and animal effluent/manure application within 'source protection zones' – areas of protection around drinking water sources. The MRA tool includes a range of soil and groundwater system types found throughout Aotearoa New Zealand, modelling various permeabilities, topographies, recharge rates, hydraulic gradients, and lithologies. The tool also includes four climate types for modelling, representing relevant regions in the country.

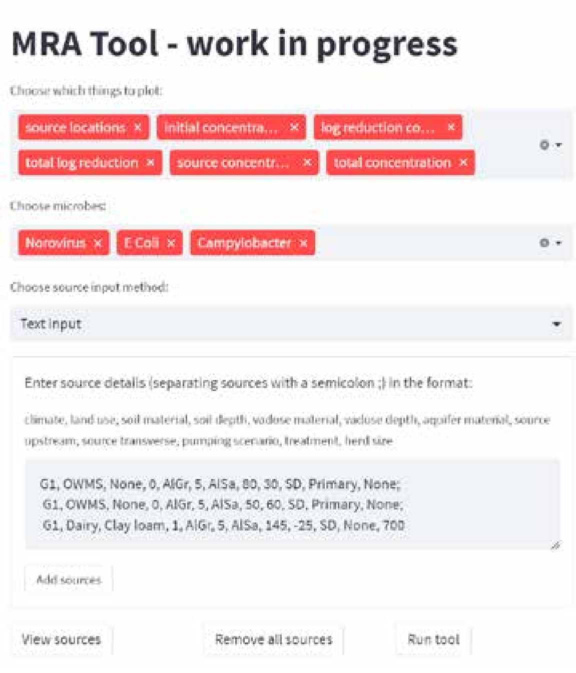
This new MRA tool offers two significant improvements over the existing guidelines: improved inputs and improved risk modelling. The tool considers more input types, including additional land-use activities, multiple on-site wastewater management systems, and supply wells that are pumped at different rates. This improves the usefulness and application of the model as well as the risk model accuracy. In addition, the MRA also provides additional information and visualisation of uncertainty to assist in understanding trade-offs in risk with different separation distances and land use activities. Instead of evaluating at only a 95% confidence level, the entire spectrum of risks can be considered, from very risk averse setting at 99%, to more risk-tolerant applications.

The MRA will benefit both land users and regional councils by providing greater guidance and certainty to stakeholders, reducing variation in assessment quality, assisting in consent processing, and avoiding duplication of effort in developing methods by individual regional councils.

The team is now building a user interface that will allow easy access and adoption of the MRA, assisting planners throughout Aotearoa New Zealand – and potentially beyond.

Fig. 15. / *Sample data input and configuration from the MRA tool, showing three land use activities upgradient of the well.*





Funded by Envirolink Tools.

Installation of denitrification wall.

Ā mātau tāngata

Our people

Murray Close – Principal Scientist

Principal scientist Murray Close is part of the Health and Environment group at ESR's Christchurch Science Centre where he leads the Groundwater team.

With over 44 years of experience in groundwater research, Murray is an expert in groundwater conditions and processes in New Zealand.

Murray has served as programme leader on a number of major research programmes including the *'Enhanced Mitigation of Nitrate in Groundwater'* research programme and the *'Groundwater Modelling of Contaminant Transport'* SSIF project. He coordinates the National Survey of Pesticides in Groundwater every four years.

Past research has ranged from developing a method for predicting reduced groundwater zones, to assessing the assimilative capacity of the groundwater with respect to different contaminants, to developing tools for testing water quality, to working on an international project looking at measuring denitrification rates in groundwater, to developing more efficient ways to sample native groundwater bacteria by detaching them from the aquifer using sonication, to trialling new methods to study the structure of alluvial gravel aquifers.

Louise Weaver – Science Leader

Dr Louise Weaver is a science leader in the Health and Environment group at ESR's Christchurch Science Centre. After university, Louise worked as a drinking-water microbiologist and then as an environmental microbiologist before completing a PhD on Protozoan parasites in wastewater at the University of Portsmouth, UK. After two postdoctoral roles at the University of Southampton, UK, she moved to New Zealand to join ESR. Louise's groundwater research focuses on identifying how land use, such as farming and waste(water) disposal, affects groundwater quality. Her work frequently assists local councils and communities in developing strategies to reduce or eliminate contaminants in their water systems. She has also been involved with a number of groundwater research projects that support both the *Our Land and Water* and the *New Zealand's Biological Heritage* National Science Challenges.

Louise leads a team that is also investigating microbial diversity in groundwater and how it can be used to assess groundwater health. The long-term goal is an inexpensive and effective tool for assessing the health of groundwater systems.

Louise is a member of the New Zealand Microbial Ecology Consortia (NZMEC), an executive committee member of NZ Hydrological Society and an honorary member of the Select Society of Sanitary Sludge Shovelers (administered by Water NZ).

Liping Pang – Science Leader

Dr Liping Pang is a science leader at ESR's Christchurch Science Centre. Liping has a PhD in Civil Engineering (University of Canterbury) and an MSc in Earth Sciences (University of Waikato). Prior to ESR, Liping was a water scientist for the Bay of Plenty Regional Council. She has been at ESR since August 1994. Her expertise is in experimental investigations into and modelling contaminant transport in porous media, particularly subsurface microbial transport.

In recent years, Liping has initiated multidisciplinary research into developing novel surrogates using biomolecule-modified particles to mimic transport and removal of pathogens *(Cryptosporidium*, rotavirus, *Legionella*) in water systems. Liping and her team have also recently developed novel synthetic DNA tracers for tracking water contamination, and 20 different DNA markers have been developed.

Liping has established an extensive database of microbial removal rates for a wide range of soils, vadose zones, and aquifer media under different environmental conditions. This database is widely used internationally to analyse water contamination risks, determine safe setback distances, and select suitable sites for land disposal of wastewater and sludge.

Liping has led three Marsden, two HRC and one MBIE Smart Ideas funded projects, and she has been a key researcher on many MBIE programmes. She has a wide network of international collaborators.

Theo Sarris – Science Leader

Dr Theo Sarris is a science leader at ESR's Christchurch Science Centre, where he leads the Water Group's modelling team. He is also an Honorary Research Associate at the School of Mathematics & Statistics of Victoria University Wellington and a Senior Associate Editor of the journal *Environmental Geotechnics.*

Theo has over 25 years of professional experience in the United States, Europe and Australasia, across research, governance and engineering consulting. He has an MSc in Civil and Environmental Engineering from Aristotle University of Thessaloniki (Greece), and an MSc and a PhD from the University of South Carolina (USA). In 2005 Theo established his own advisory services company in Greece, specialising in groundwater resources management and served as Senior Science Advisor to the Greek Ministry of Environment, Energy and Climate Change. In 2013, he moved to NZ to lead the groundwater modelling team of Consulting Engineering firm Beca.

In late 2016, Theo joined ESR's Groundwater Research Group, where he leads large groundwater research projects on topics such as managing contamination risk for groundwater wells, engineering mitigation options for reducing nutrient levels in groundwater and integration of AI tools in groundwater hydrology. He works closely with iwi, communities and regional councils to develop practical solutions and tools for the protection, safety and resilience of their groundwater resources, and he is the author and co-author of numerous technical and research reports and papers.

Theo is the current chair of the 2023 Australasian Groundwater Conference and served as president of the New Zealand Chapter of the International Association of Hydrogeologists until 2022.

Laura Banasiak – Senior Scientist

Dr Laura Banasiak is a senior scientist in the Health and Environment group at ESR's Christchurch Science Centre. Laura has a ME in Civil Engineering – Research from the University of Wollongong, Australia and a PhD in Environmental Engineering from the University of Edinburgh, UK. Laura has held several postdoctoral academic positions including Vice Chancellor's Postdoctoral Research Fellow in Geotechnical Engineering, University of Wollongong, Australia; Research Assistant, University of Tokyo, Japan, and Lecturer in Chemical and Process Engineering, University of Canterbury, New Zealand. Her expertise is in the use of engineering mitigation strategies for groundwater contamination including the use of permeable reactive barriers for the treatment of acid sulphate soils. She was appointed to the Stockton mine assessment expert reference group and co-authored a technical report for Treasury.

Laura joined ESR's Groundwater Research Group in 2017, where she has been involved in several groundwater research projects such as engineering mitigation options for reducing nutrient levels in groundwater, predicting groundwater redox status at a national scale, and the National Survey of Pesticides in Groundwater. She is currently collaborating with researchers from the University of Canterbury on the environmental implications of recycling end-of-life tyres into seismic resilient foundations.

Andrew Pearson – Senior Scientist

Dr Andy Pearson is a senior groundwater scientist at ESR's Christchurch Science Centre. He has a PhD in environmental geochemistry from the University of Waikato, and prior to ESR worked as a Groundwater Scientist at Environment Canterbury. Here he wrote and contributed to technical reports on groundwater quality and provided groundwater technical advice to Consents Planners and decision-makers.

Andy's research focuses on determining and remediating the impacts of land use (particularly nitrate pollution) and waste disposal on Aotearoa New Zealand's groundwater quality. Andy aims to use research findings to assist resource management decision-making and inform approaches to environmental and public health protection.

Bronwyn Humphries– Senior Scientist

Bronwyn Humphries is a Senior Scientist at ESR's Christchurch Science Centre. Bronwyn has a MSc from the University of Canterbury and her thesis investigated the use of Kiribati coral sands as a filter medium for domestic effluent treatment. Her career in New Zealand and overseas has included working for a regional council and an environmental consultant as well as a water and sanitation aid programme manager in Ethiopia.

Bronwyn's expertise and passion lies in groundwater science with a particular interest in finding solutions for safe drinking water and human wastewater treatment and disposal. Since joining ESR in 2011 she has developed a keen research interest in groundwater and wastewater microbiology and the implications for human health. Bronwyn is also the Technical Manager of the NZ Land Treatment Collective (www.nzltc.org.nz) and works to provide its members with up-to-date information on land treatment technologies and research. She works closely on land treatment issues with research organisations, universities, district and regional councils, government departments, environmental and engineering consultants and tangata whenua. Her current research focuses on on-site wastewater management systems (decentralised wastewater) and their impact on groundwater quality, while also assisting councils and industry to navigate the changing Three Waters environment and climate change.

The scientists also acknowledge the tireless support of their wider team of scientists and technicians who have contributed to this research.

Ko wai mātou

About us

Science to keep our people well, communities safe and environment healthy.

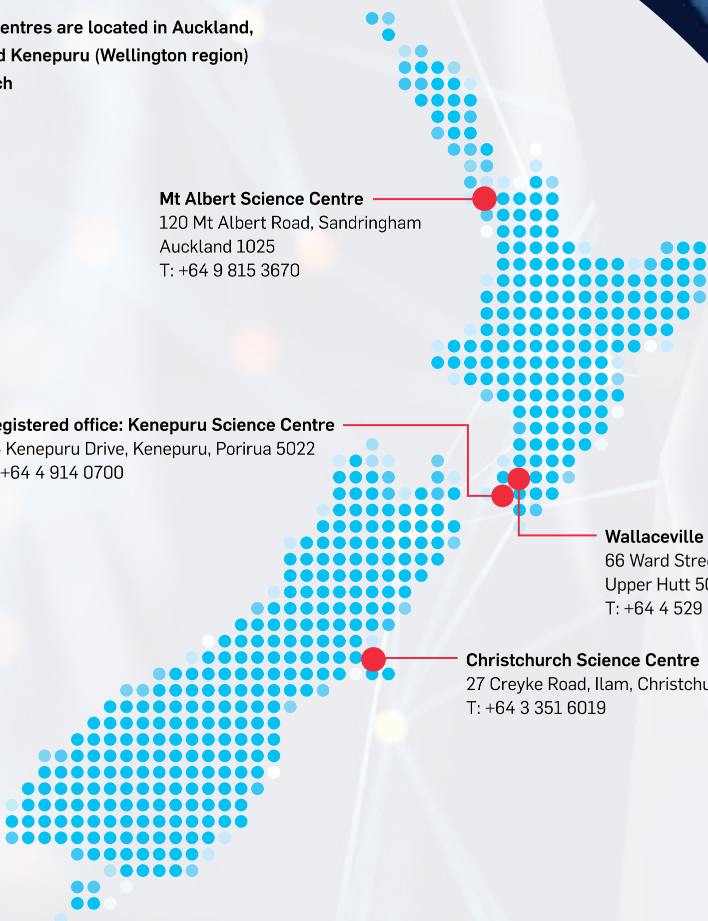
ESR is a New Zealand Crown Research Institute specialising in science for communities. We work alongside local and national authorities, national and international research organisations and iwi partners to help improve the safety of, and contribute to, the economic, environmental and social wellbeing of people in New Zealand. We identify infectious diseases and strengthen pandemic preparedness; provide world-class genomics science in wastewater testing, food genomics and antimicrobial resistance; contribute expert forensic science to justice systems; and manage and monitor the safety and sustainability of the water and environment we rely on.

Our water and environmental health experts specialise in investigating water quality and identifying possible sources of water contamination. We aim to reduce the burden of waterborne illness outbreaks, address public health risks and contribute to the sustainable use and management of water and wastewater systems. We work with Māori and iwi partners to improve how their wai (water) is restored, managed and protected. And we work with Pacific Island countries to support safe water supply as the impacts of climate change intensify.

The groundwater team brings together people with skills from genomics to hydrology to modelling to biotechnology to deliver on ESR's research aims. Our research on groundwater health and management helps us focus on local issues while also contributing to a global understanding of groundwater. Our high-quality data, contamination tracking technology, models, and management tools inform resource management policy that improves groundwater and wider freshwater quality and prepares for the effects of climate change.

For more information about ESR visit us at **www.esr.cri.nz**

ESR's science centres are located in Auckland, Wallaceville and Kenepuru (Wellington region) and Christchurch



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