SOURCE WATER RISK MANAGEMENT AREA MODELLING FOR GROUNDWATER: ISSUES AND UNCERTAINTIES

Helen Rutter, Jane Alexander (Aqualinc Research Ltd) and Catherine Moore (GNS)

ABSTRACT

The first barrier for preventing waterborne illness is to protect the drinking water sources from contamination. To do so requires delineation of source water risk management areas (SWRMAs), within which activities are controlled. The SWRMAs reflect the risk of source water contamination based on the time for contaminants to travel to the abstraction point, and also the time needed for some contaminants (e.g., bacteria) to attenuate or become inactive. The National Environmental Standards for Drinking Water (2007) (NES-DW) were intended to support source water protection by providing national direction on how to manage activities that could impact the quality of treated drinking water. In the recent review of the NES-DW there was found to be significant variation in the methods used to define those zones.

A default methodology for delineating ‘source water risk management areas’ (SWRMAs) has been proposed to identify areas where activities have a higher likelihood of affecting source water (Lough et al., 2018). However, default zones may be too conservative in some cases, and not sufficiently conservative in others. There is a fine balance with conservatism. If the SWRMA is over-conservative, it could limit or restrict land use activities on highly productive land or lead to unnecessary barriers to the consenting and establishment of safe new community water sources. If not sufficiently conservative, then activities could be allowed within the SWRMA that could cause contamination of the source, or new sources could be allowed that are at risk. Simple approaches to defining SWRMAs must use a higher degree of conservatism than more robust methods. However, where risks are high, and/or there are large populations supplied by a well, then modelling-based methodologies have merit.

While SWRMA guidance (Moreau et al., 2014a) has referred to numerical modelling, there has been a lack of specific guidance on what makes a good model for SWRMA purposes. In particular, the prediction context is important: this relates to the level of risk being addressed (i.e., the risk that people could get sick; the loss of land use capability; etc.). Existing groundwater models may not be suitable for SWRMA delineation, and a poorly-constructed/constrained model may be worse than a simple/default method. Uncertainty quantification (UQ) and sensitivity analyses are a central part of any risk-based modelling, and predictions made by a model need to be accompanied by assessments of their uncertainties. Rutter and Moore (2021) developed guidelines for risk-based minimum model design and uncertainty quantification, to provide an indication of modelling and UQ approaches to be used.

This paper outlines different approaches to SWRMA delineation and covers some of the issues and pitfalls that can occur.

KEYWORDS

Source water risk management; groundwater; modelling; uncertainty

PRESENTER PROFILE

Dr Helen Rutter is a Principal Hydrogeologist with Aqualinc Research Ltd, having over 25 years' experience working in hydrogeology in the UK, Botswana, and New Zealand. She has in-depth understanding of physical hydrogeology, including resource assessment, recharge processes, groundwater flooding, catchment characterisation, geology and geochemistry. She has carried out extensive research into the hydrogeological impacts of the Canterbury Earthquake Sequence, including a Marsden-funded research project. She has an increasing interest in water quality, and transport of nitrates through groundwater. She is also involved in developing methods to delineate source protection zones for drinking water supplies.

1 INTRODUCTION

1.1 BACKGROUND

The National Environmental Standards for Drinking Water (2007) (NES-DW) provide national direction on how to protect communities by preventing waterborne illnesses originating from source water contamination. This is achieved by defining Source Water Risk Management Areas (SWRMAs, previously referred to as Source Protection Zones or SPZs), which are designed to protect drinking water sources by delineating areas on the land surface where contamination has the potential enter the drinking water supply. Activities are controlled within SWRMAs based on the risk of source water contamination, which is determined by the time for contaminants to travel to the source abstraction point, and the time for some contaminants to attenuate or become inactive.

The technical guidelines for delineating SWRMAs recommend three levels of activity management to protect drinking water sources from contamination1. The levels are:

- **SWRMA 1**: This is the immediate area around the source intake where contaminants have the potential to directly impact the intake structure. Strict control of land-use activities is required in this area. For a groundwater source this is the immediate well-head area.
- **SWRMA 2**: This is an intermediate area in which specific land-use activities or discharges which may contaminate the water source will be controlled. For groundwater sources, the travel velocity of any contamination which enters the contributing source waters is likely be relatively slow, meaning the purpose of the SWRMA is to provide contaminant attenuation. The SWRMA is sized such that, if a contaminant discharge occurred outside the SWRMA boundary, the water would travel through the groundwater system for a sufficient time that microbial contaminants would likely attenuate or become inactive by the time the contaminated water reached the drinking water abstraction point.
- **SWRMA 3**: This is the wider area, within which non-point sources from land use, cumulative effects of small-scale discharges, and large-scale discharges may need to be managed. This area is also intended to encapsulate more persistent contaminants which may not attenuate significantly as they travel through the groundwater system, such as nitrates, pesticides, and some emerging contaminants. For a groundwater source this is the total capture zone that could contribute water to the well.

This paper focuses on approaches to defining SWRMA 2 for groundwater sources. The technical guidelines recommend that a 1-year travel time to the well intake is used to achieve sufficient attenuation of microbial contaminants. A recent review of the guidelines for defining SWRMAs has shown there are a wide range of methods used to define the 1-year travel time, both nationally and internationally, with varying degrees of accuracy and resource requirements (Lough et al., 2018).

1.2 MAPPING AND MODELLING PHILOSOPHY

Before commencing SWRMA delineation, it is valuable to consider the underpinning philosophy of mapping and modelling SWRMAs. In delineating SWRMAs, there is a balance that must be achieved between protecting human health and maintaining productive land use. The possible unwanted outcomes when delineating SWRMA 2 are that the SWRMA is either too limited, allowing risky land use within the vicinity of the source and putting community health in danger, or too extensive, taking valuable productive land out of circulation. The desired level of confidence in avoiding these risks contributes to the selection of a SWRMA assessment approach. A simple default method, with demonstrably conservative uncertainty limits, may be able to be used to avoid generating SWRMAs that are too small. If the simple default approach is deemed to result in undue land-use restrictions, there may be a motivation for moving to a more complex model, reducing the uncertainty and making full use of relevant field data where it is available.

Appropriate model selection is dependent on the prediction context. For SWRMA delineation, this relates to the level of risk being addressed (i.e., the risk that people could get sick or that land use capability could be lost). The role of a model in this context is to both robustly quantify the uncertainty of an SWRMA and to reduce this uncertainty to the extent possible given the available data. This should be the basis for any model design (Doherty and Moore, 2020). Rutter and Moore (2021) identified three components of the prediction context that may influence the selection of an appropriate modelling approach for delineating SWRMAs:

1. The number of people being supplied by the drinking water source, which will impact the pumping rate required and therefore the size of SWRMA 2. The supply population may also influence the depth of the well, as larger supplies are generally more likely to justify the expense of a deep supply bore which penetrates a more secure confined aquifer. This will impact the size and location of the SWRMA in relation to the source.
2. The hydrogeological context, including the aquifer geology, the prevalence of preferential flow paths and heterogeneities, and variability in environmental conditions (e.g., cumulative pumping effects, changes in flow gradients, floods and droughts).
3. The availability of data to inform model parameters representing aquifer properties, heterogeneity, and connectedness, and the extent to which available data may be able to reduce the uncertainty surrounding the aquifer parameters used in the SWRMA delineation model. Data may include tracer tests in similar strata, groundwater age estimates which may inform recharge provenance, and more traditional groundwater model data such as pumping data, groundwater levels, and stream flow gauging.

For example, the prediction context may be considered reasonably simple if a well is screened in a homogeneous unconfined sand aquifer and used to supply a single dwelling. The pumping rate required to supply a single dwelling would be low, and hence difficulties in representing aquifer boundary conditions can be ignored. Even though a demonstrably conservative allowance for uncertainty would be required for a simple model, this would not result in an overly large SWRMA because of the low pumping rate. Hence, only a small area of land would be affected by this necessary conservatism. In this simple context, a model may be based on expert knowledge and site characterisation information.

In contrast, a prediction context may be considered more complex where a town supply well is screened within an alluvial gravel aquifer that contains rapid, high-permeability transport pathways. In this context, the pumping rate will be larger because of the bigger population being serviced. The model will therefore need to represent more distant aquifer boundaries (such as surface features) and consider how these boundaries will change over time. The heterogeneity that allows rapid transport of pathogens in this type of aquifer will also need to be accounted for using stochastic methods, informed by expert knowledge and site characterisation information. In this more complex context, a model may also be informed by historical observations of the aquifer system using history matching methods, if this will reduce the uncertainty of the SWRMA delineation.

Different types of models may be adopted in these different prediction contexts, as conceptually shown in Figure 1.

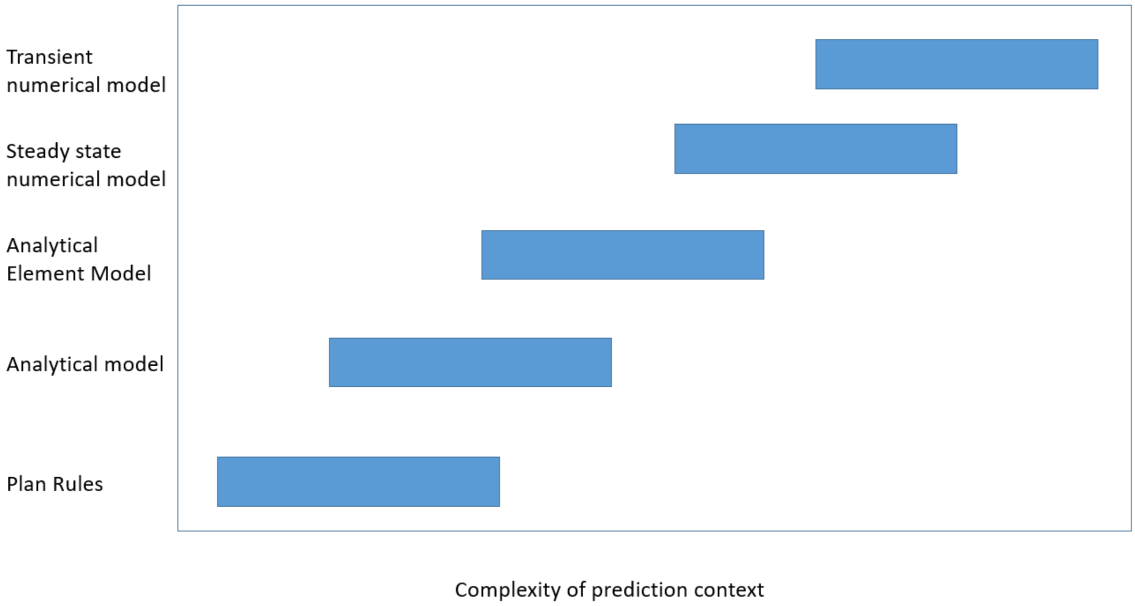

Figure 1. Complexity of prediction context

2 APPROACHES TO DELINEATING SWRMA 2 FOR GROUNDWATER SOURCES

The section explores some of the methods which have been identified for delineating SWRMA 2 for groundwater sources in order of increasing complexity.

2.1 ARBITRARY RADIUS METHOD

This method uses a fixed radius around the well to define SWRMA 2. This is the least certain method for defining a SWRMA, but it is relatively easy, inexpensive, and does not require any knowledge of the hydrogeological parameters at the source location.

Work by Blaschke et al. (2016) suggests that microbes are unlikely to travel more than 2.5 to 3 km in most aquifer systems. As such, it is generally accepted that a 2.5-kilometre radius is sufficient to assume full microbial attenuation, and this approach is recommended by the technical guidelines for delineating SWRMAs as a default approach when no data on the aquifer parameters is available. It is also recommended that SWRMA 2 extents obtained using more complex methods are limited to a maximum distance of 2.5 km from the source, except in aquifers where little attenuation is known to occur, such as karst aquifers.

2.2 CALCULATED RADIUS METHOD

This method uses a calculated radius around the well intake to delineate SWRMA 2 based on abstraction, aquifer parameters, and recharge. One approach for defining a calculated radius is summarised in Kerr et al. (2018). For sources in confined aquifers the radius is calculated as:

$$r = \sqrt{\frac{Qt}{\pi n b}} \quad (1)$$

Where Q is the source abstraction rate (m3/year), t is the travel time (1 year for SWRMA 2), n is the effective porosity of the aquifer, and b is the screen length of the source (m).

For sources in unconfined aquifers the radius is calculated using the smaller of equation (1) and:

$$r = \sqrt{\frac{Q}{\pi \cdot recharge}} \quad (2)$$

A possible method for determining the inputs to equations (1) and (2) is summarised in Kerr et al. (2018). Aquifer lithology may be used as a proxy for assigning effective porosity where it is not known.

This method bases SWRMA 2 on site-specific data but does not account for the groundwater flow direction.

2.3 ANALYTICAL METHODS

Simple analytical approaches use formulae to calculate the contributing area based on abstraction at a constant rate and assuming known piezometric surface and aquifer properties. Analytical methods generally account for the flow direction in the groundwater system, and commonly define the SWRMA as a parabolic area with a stagnation point downgradient of the abstraction point. An example schematic of a parabolic zone of contribution is shown in Figure 2. Analytical equations are used to calculate the distance to the downstream stagnation point, the 1-year travel distance, and the SWRMA width at the source. Rules of thumb are used to estimate the SWRMA width at the upstream boundary, with the aim of accounting for uncertainties in flow direction and dispersion within the aquifer system.

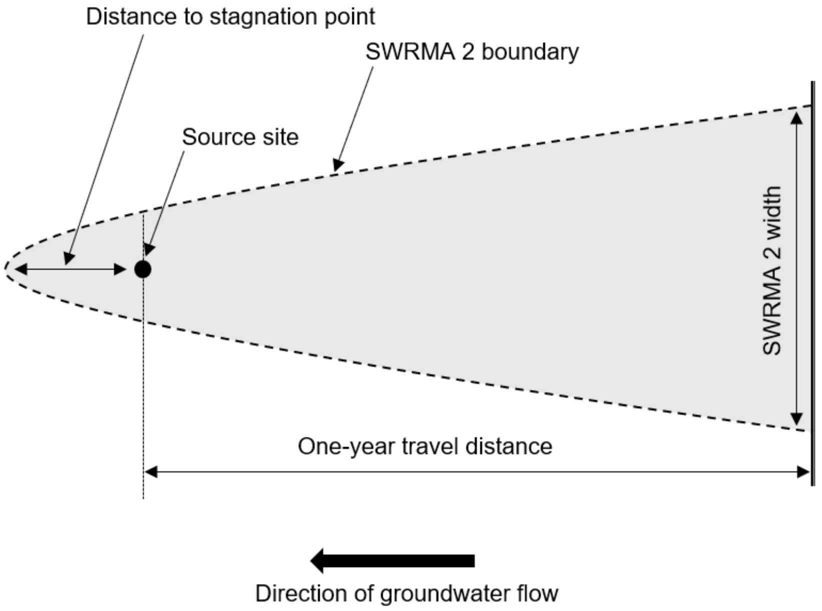

Figure 2. Schematic of SWRMA 2 determined by analytical equations

Numerous software packages exist to generate zones of contribution based on analytical equations, such as WHPA, created by the EPA, and WINFLOW, created by the Scientific Software Group. Options for analytical equations on which to base SWRMA 2 include the uniform flow equation (Moreau et al., 2014b) and the Hunt (2012) drawdown equations.

Input parameters generally include the abstraction rate, hydraulic gradient, aquifer hydraulic conductivity, aquifer transmissivity, aquifer porosity, and the groundwater flow direction. Additional inputs may be required if the analytical equations incorporate stream depletion or flow through overlying confining layers.

The influence of a confining layer or an upward hydraulic gradient may mean that there is no surface expression of the one-year time of travel. As identified by the guidelines, in some circumstances, such as deep confined aquifers with low permeability overlying strata, it may take more than 1 year for contaminants to travel both horizontally from the recharge zone and vertically from the land surface.

The hydrogeological parameters used in analytical methods are generally not widely available on public databases, limiting the number of sites where the analytical method can be implemented using site-specific groundwater data. Some parameters in the equations may be represented using proxy values which can be obtained from datasets with nation-wide coverage, including:

- Hydraulic gradient estimated from topographical slope (Moreau et al., 2014b)
- Hydraulic conductivity estimated from aquifer tests at bores within the 50-year TOT radius, or from the representative values based on an aquifer lithology lookup (Moreau and Bekele, 2015)
- Transmissivity estimated from aquifer tests at bores within the 50-year TOT radius, or from the representative values based on an aquifer lithology lookup and an assumed screen length (transmissivity = hydraulic conductivity * screen length)

Analytical methods can be highly accurate if the required data is available and the groundwater region lacks hydrogeological complexities. A lack of confidence in parameter values can be allowed for by using conservative estimates of aquifer parameters and adjusting values within appropriate tolerance limits, e.g., by ±25% as suggested by Moreau et al. (2014a). It is also useful if the variability of the piezometric surface and flow direction across seasons can be assessed. If needed, any variability that is identified can be used to develop an envelope of SWRMAs, with the worst-case (most conservative) area being identified by the outer limit of all overlapping areas.

2.4 NUMERICAL MODELLING METHODS

Numerical models can be used to simulate two- or three-dimensional flow and contaminant transport. These models can be run as steady-state (constant) or transient (time-varying) models. They can accommodate more complex flow and transport conditions, including spatially-variable aquifer properties, changes between confined and unconfined conditions, multiple wells and variable pumping rates. They also include non-uniform boundary conditions such as recharge, rivers, drains, no-flow, and coastlines, and are usually built over larger study areas (including far-field boundaries) than simpler models. Numerical models can be used to delineate multiple capture zones and can also account for interference between pumping at different locations.

Numerical models have not previously been developed with the specific purpose of SWRMA delineation but have been used where a model already existed. Their use may also be considered where there is a need to understand uncertainty clearly or where there is a concern about minimising the SWRMA extent, e.g., in areas with high land value.

Numerical models may be two- or three-dimensional, steady-state or time-varying, and deterministic or stochastic. Stochastic methods are preferred in this application, to ensure the uncertainty associated with the SWRMA delineation is clearly communicated. The approach involves discretising the aquifer system into a grid or mesh of cells, which are used to calculate changes in water storage. Common numerical modelling approaches include finite difference, finite element, and finite volume models. Software packages such as MODFLOW and FEFLOW are available for implementing numerical models.

Numerical models require a good conceptual understanding of the hydrogeological setting, including estimates of hydraulic conductivity, porosity, aquifer geometry, saturated thickness, hydraulic gradient, pumping rates, recharge rates, river/stream/lake locations, and bed properties. Parameter variance terms and covariance matrices allow the spatial correlation between parameters with increasing separation distance to be represented in uncertainty analyses.

Numerical methods allow a more realistic representation of aquifer heterogeneity and its boundary conditions. Therefore, they are able to represent the uncertainty of model predictions more realistically and reduce the uncertainty by more effectively extracting information from available data. Because of this, numerical models do not need to adopt the greater conservatism and unnecessarily large SWRMAs that are often required of simpler models.

3 APPROACHES TO UNCERTAINTY ANALYSIS

A key point to consider in any SWRMA delineation approach is uncertainty analysis. All SWRMAs are delineated based on incomplete knowledge. Aquifer parameters cannot be known at every point in the system, and experimental and field data is also corrupted to a degree by measurement and interpretation errors. This means the SWRMA extent cannot be determined with certainty. Uncertainty quantification (UQ) is, therefore, a central part of SWRMA delineation, and predictions made by any delineation approach need to be accompanied by assessments of their uncertainties.

UQ describes how uncertain a prediction is given the uncertainty in model parameter values, using the full joint probability distributions of a parameter suite. This accounts for the uncertainty of the parameter values, and any correlation between them. Depending on the model design, UQ approaches can be undertaken on the basis of prior parameter distributions (i.e., prior to any history matching), or on the basis of posterior parameter distributions (as defined by some history matching effort).

The prediction context referenced earlier dictates which delineation approach and UQ should be adopted. For instance, in a low-risk context, an appropriately designed simple model may be deployed to delineate a SWRMA, accompanied by an “engineering safety margin”. An appropriately designed simple model, plus conservative predictive safety margins, allows a rapid SWRMA delineation, with the only requirement being that the safety margin is demonstrably conservative. This conservatism can be difficult to verify, e.g., the differing approaches used by Tonkin & Taylor and HBRC in Hastings, where an analytical element model and numerical modelling approach resulted in very different one-year capture zones (Rutter and Moore, 2021).

More complex models can refine the SWRMA delineation through greater use of expert knowledge and may also mean that the uncertainty associated with the SWRMA can be quantified. This is because a complex model can more accurately represent hydraulic processes and properties, which means it is possible to explore the repercussions of less-than-full knowledge of these details. The need to ascribe a conservative predictive safety margin to the model prediction is therefore replaced with an uncertainty assessment of the capture zone that reflects all of the information available. However, increasing modelling complexity and incorporating UQ can be computationally expensive tasks. It is therefore recommended that model design and UQ are considered early in the SWRMA delineation project, to assess which prediction context the SWRMA delineation is in.

Approaches for quantifying uncertainty include:

- **Worst case analyses:** This approach considers only the conservative end of parameter probability distributions. This may be as simple as introducing an engineering safety margin, such as the ±25% referenced earlier.
- **Propagation of error methods:** This is the most common form of uncertainty analysis, whereby a mean and standard deviation are used to express the uncertainty of the SWRMA delineation. These methods are also called first order, second moment (FOSM) methods. A more complete expression of the uncertainty is calculated on the basis of a prediction-parameter sensitivity matrix and a parameter covariance matrix. This UQ method assumes a linear relationship between parameters and predictions, allowing an analytical solution to be used, which can in some cases offer a rapid UQ option.
- **Monte Carlo (MC) assessments:** This approach allows realisations of multiple possible subsurface heterogeneities to be represented. The delineation is generated with each of these realisations which are collated into a probability distribution. This approach is considered the most correct, but can be slow to complete, particularly if history matching is used to transform a prior parameter distribution into a posterior distribution.
- **Hybrid methods:** This approach has been developed to address the computational burden associated with the MC approach. The most recent of these more efficient technologies is the ensemble smoother technology (White, 2018), which within a few thousand model runs can transform a prior parameter probability distribution into a posterior, with much less effort than previously.

There are four categories of model inputs which have associated uncertainty and therefore need to be represented in uncertainty analysis:

- **Model structure**: Includes flow geometry and model inflow and outflow boundaries.
- **Parameter**: Includes hydraulic conductivity and effective porosity.
- **Stress**: Includes pumping rate and recharge rate.
- **Data**: Includes piezometric gradient and flow direction.

For stress and data inputs, time-varying or average values may be used, with time-varying values being particularly important where extreme events may impact the extent of the SWRMA.

4 MODEL DESIGN AND UNCERTAINTY QUANTIFICATION

Table 1 to Table 3 summarise how the three components of the prediction context identified by Rutter and Moore (2021) may be used to inform the complexity required in model approach and UQ. The criteria are grouped by population served, hydrogeological complexity, and information content.

Table 4 combines the groupings defined into a risk-based model design and uncertainty quantification framework. Some of the categories are somewhat arbitrary, and a more formal risk analysis in different hydrogeologic contexts could be useful to refine these categories. It is also important to recognise that in some cases practitioners may already have existing models available that they would like to use. However, the limitations of existing models need to be understood, with the focus being on establishing a model that is fit for purpose.

Table 1: Pumping rate estimate for the population served

Category	Pumping rate	Complexity
Small community (up to 500 people)	10-100 m^3/day	Low
Large community – Township (up to 50,000 people)	100-10,000 m^3/day	Moderate
Municipal city supply	>10,000 m^3/day	High

Table 2: Hydrogeological complexity

Category	Criteria	Complexity to be accounted for implicitly or explicitly in model design and UQ
Confinement	Artesian head criterion	Low
	No artesian heads	High
Surface Water Boundary conditions	Proximal streams/surface waters	High
	No proximal surface waters	Low
Heterogeneity	Connected high permeability pathways (Alluvial gravel, karst and fractured rock)	High
	Moderate (Sandstone and non-karstic limestone)	Moderate
	Homogeneous (Alluvial sand, pumice sand, coastal sand)	Low

Table 3: Data that could be available and used to reduce SWRMA 2 delineation uncertainty

Historical measurement data	Information content
Tracer test in location	High
Aquifer flow information, boundary conditions, recharge rates, and how these change over time	Moderate

Limited	Much of the model information must come from expert knowledge or site characterisation data

Table 4: Risk- based minimum model design and uncertainty quantification framework

Pumping rate	Hydrogeological complexity	Information content	Minimum model design complexity plus UQ
Low (Small communities)	Low – moderate	Any	Appropriately designed simple models* combined with a demonstrably conservative engineering safety margin or mean plus standard deviation to express SWRMA uncertainty. Do not history match as models are too simple, but check that the model outputs do not contradict available data or site conceptualisation information.
	High	Any	
Moderate-High (Large communities-Townships-Cities)	Low - moderate	Any	Appropriately designed simple models, ensuring that model boundary conditions are well represented. Combined with FOSM or Monte Carlo methods to express SWRMA uncertainty. If prediction-relevant data is available and using numerical models, history match to reduce the uncertainty of capture zones to the extent the data allows.
	High	High	More complex numerical model with structure appropriate to support a highly distributed parameterisation, supported by a geostatistically-based parameter covariance matrix. Use FOSM or Monte Carlo or hybrid Monte Carlo methods to quantify SWRMA uncertainty. Use history matching to reduce the uncertainty of capture zones to the extent the data allows.
	High	None	More complex numerical model with structure appropriate to support a highly distributed parameterisation. Parameterisation may be supported by a geostatistically-based parameter covariance matrix, or using other advanced geostatistical methods to better characterise aquifer connectivity.**

*The appropriateness of a simple model is context-specific. Identifying the appropriateness of various simple model designs in anisotropic and heterogeneous aquifers is the subject of current research (Section 6).

** In their current implementation, advanced geostatistical representations of aquifer heterogeneity cannot be used in history matching contexts without corrupting the geostatistical realism, and hence these methods are best deployed where history matching is not possible.

5 ISSUES AND PITFALLS

Different approaches to delineate SWRMAs have been taken by various organisations over recent years, with associated issues and pitfalls emerging in the process. Several points are worth noting:

- The assumption that simpler methods produce the largest capture zones and are therefore more conservative may not be true. Similarly, default zones may be under- or over-conservative. For example, Canterbury's draft source protection zone guidelines recommend a default fixed radius of 100 m around a well for deep confined wells, when numerical modelling has shown that in some cases the one-year travel time may not reach the surface. Conversely, an unconfined well in the depth range of 10-30 m has an up-gradient limit of 1,000 m and cross-gradient width of 200 m, with a similar depth well in a confined aquifer having a 100 m radius. Both these examples have been found to be under-conservative compared to generating SWRMAs using a an analytical approach
- A bespoke risk management area defined by a numerical model may be "better" than a default area, either in terms of the level of protection offered, or the impact on existing land-use activities. However, this is not always the case: a numerical model that is poorly conceptualised, overly simplistic, uses poor input data, or is constructed for a different purpose, may produce results that are worse than some of the more basic methods available.
- Approaches which have been shown to produce realistic zones in certain case study settings may not be appropriate nation-wide. For instance, the uniform flow equations presented in Moreau et al. (2014b) and recommended by the technical guidelines (Lough et al. 2018) as an analytical approach for defining SWRMA 2 were shown to generate realistic SWRMAs in a range of case studies. However, in trialling the method, we found that it can result in unrealistically long, thin SWRMAs in aquifers with relatively high transmissivity and low effective porosity, such as the Canterbury Plains alluvial gravels. Under such conditions, groundwater is modelled to occur rapidly along long, thin flow lines.
- Detached protection zones (where the SWRMA extent defined at the surface does not include the source) can occur in certain hydrogeological settings. This eventuality cannot be represented by 2D modelling approaches, which may result in a surface expression of the SWRMA which does not occur in reality. Modelling in 3D allows this behaviour to be visualised and understood.
- UQ and sensitivity analysis are often included as an afterthought. However, they should be considered at the beginning of a project as part of the method design.
- A good fit with data is assumed to mean good predictive capabilities. However, a good fit to heads and stream flow rates may not correspond to accurate prediction of contaminant transport times. UQ should also take into account aquifer heterogeneity that will not be well informed by heads and flows.
- Model design is generally opportunistic rather than based on the risk-data context. In some cases numerical models have been implemented based on the misconception that they are always more sophisticated tools, rather than considering whether there is a current model build that may be suitable for SWRMA delineation.
- In the case of numerical models, the need to account for local effects around the well requires either refining the entire model grid or switching to an unstructured grid approach, adding to the computational load associated with running the model.

- The time-varying nature of aquifer system parameters, such as the piezometric gradient and groundwater flow direction, is critical to consider when defining SWRMAs. This is particularly true in cases where the SWRMA is relatively narrow and an adjustment in the groundwater flow direction may significantly affect the area covered.

Any SWRMA delineation approach will never be able to map accurately the exact one-year travel time. The important factor is to safeguard human health, whilst also ensuring that land use is not unnecessarily restricted. The use of appropriate models and uncertainty assessment will facilitate this.

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