Administrative Limits for Tritium Concentrations Found in Non-Potable Groundwater at Nuclear Power Facilities

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Abstract

Currently, there is a regulatory limit available for tritium in drinking water, but no such limit for non-potable groundwater. Voluntary administrative limits for site groundwater may be established at nuclear power facilities to ensure minimal risk to human health and the environment, and provide guidance for investigation or other actions intended to prevent exceedances of future regulatory or guideline limits. This work presents a streamlined approach for nuclear power facilities to develop three tiers of administrative limits for tritium in groundwater so that facilities can identify abnormal/uncontrolled releases of tritium at an early stage, and take appropriate actions to investigate, control, and protect groundwater. Tier 1 represents an upper limit of background, Tier 2 represents a level between background and Tier 3, and Tier 3 represents a risk-based concentration protective of down-gradient receptors.

1. Introduction

There is a regulatory limit available for tritium in drinking water (applicable to potable groundwater, [1] and [2]) but no such limit for non-potable groundwater. Voluntary threshold limits (administrative limits) for site groundwater should be established at nuclear facilities, as a due diligence measure, to ensure minimal risk to human health and the environment. These administrative limits provide early indicators to investigate and implement other actions that are intended to prevent exceedances of future regulatory or guideline limits. This paper presents a methodology for nuclear power facilities to develop tiered administrative limits for tritium in groundwater to identify, at an early stage, abnormal/uncontrolled releases of tritium, and take appropriate actions to investigate, control, and protect groundwater. This approach can be readily adapted according to site-specific considerations. A more detailed discussion and example applications of the methodology are presented in COG-10-3069 [3].

The Canadian Nuclear Safety Commission (CNSC) is looking to standardize their approach to groundwater protection practices at nuclear facilities. In discussion paper DIS-12-01, the CNSC proposes that licensees and applicants "implement controls to ensure that groundwater is protected as a resource, conduct end-use analyses to set appropriate criteria for groundwater protection, [and] implement appropriate groundwater monitoring programs" [4]. The methodology outlined in this paper provides a standardized approach that could be used to meet the CNSC's objective to establish greater consistency in groundwater protection practices.

Although this paper specifically focuses on tritium, the generic tiered approach could be applied to other contaminants.

2. Review of Existing Approaches to Groundwater Standards

A review of current approaches to development of groundwater standards was performed for Europe, Netherlands, Australia, United States, Canada, and Ontario. A detailed summary is included in COG-10-3069 [3]. Both the Ontario and European approach to development of groundwater standards recognize that receptor locations are usually some distance away from groundwater monitoring locations, and make explicit allowance for attenuation along the groundwater path. The approaches in Ontario and Europe both allow for dilution in the surface water receptor.

All jurisdictions reviewed either define ambient background groundwater concentrations, or recommend site-specific determination of background, so that a departure from background concentrations can be recognized and appropriate action taken. Both the Netherlands and European approach involve a tiered system of groundwater standards, ranging from background levels to receptor risk-based levels, with an intermediate warning level.

3. Tiered Approach for Setting Groundwater Limits

The proposed approach to setting administrative levels for tritium in groundwater at nuclear power facilities involves three Tiers of groundwater concentrations, as follows:

- Tier 1: an upper limit of background (ULB) level, at which departure from normal is recognized, and investigative actions are initiated, in a graded manner;
- Tier 2: a level between background and the risk-based concentration, at which mitigation plans should be made and implemented in time to be successful; and
- Tier 3: a risk-based concentration (RBC) considered protective of down-gradient receptors, and representing a value never to be exceeded at the monitoring point.

The tiered approach sets out a methodology for nuclear power facilities that can be readily adapted according to site-specific considerations, while maintaining a consistent approach. Figure 1 outlines the recommended three-tiered approach to be applied when determining the status of wells. Well status is determined relative to the three tiers, for both older and newer nuclear power facilities, based on identification of a potential tritium source. Atmospheric release of tritium at nuclear facilities is generally a continuous release. Groundwater wells at older facilities will likely be in dynamic equilibrium with the atmospheric tritium plume. However, depending on the depth to well screen, a newer facility may not have had time to reach dynamic equilibrium. As such, an increasing trend in tritium concentration in groundwater will be observed, but may result from atmospheric releases of tritium rather than from a point-source leakage from the facility. Actions taken to identify tiers in a newer facility are described in Section 3.1.4. If no potential source has been identified the method outlined in Section 3.1.5 is appropriate for identifying tiers.

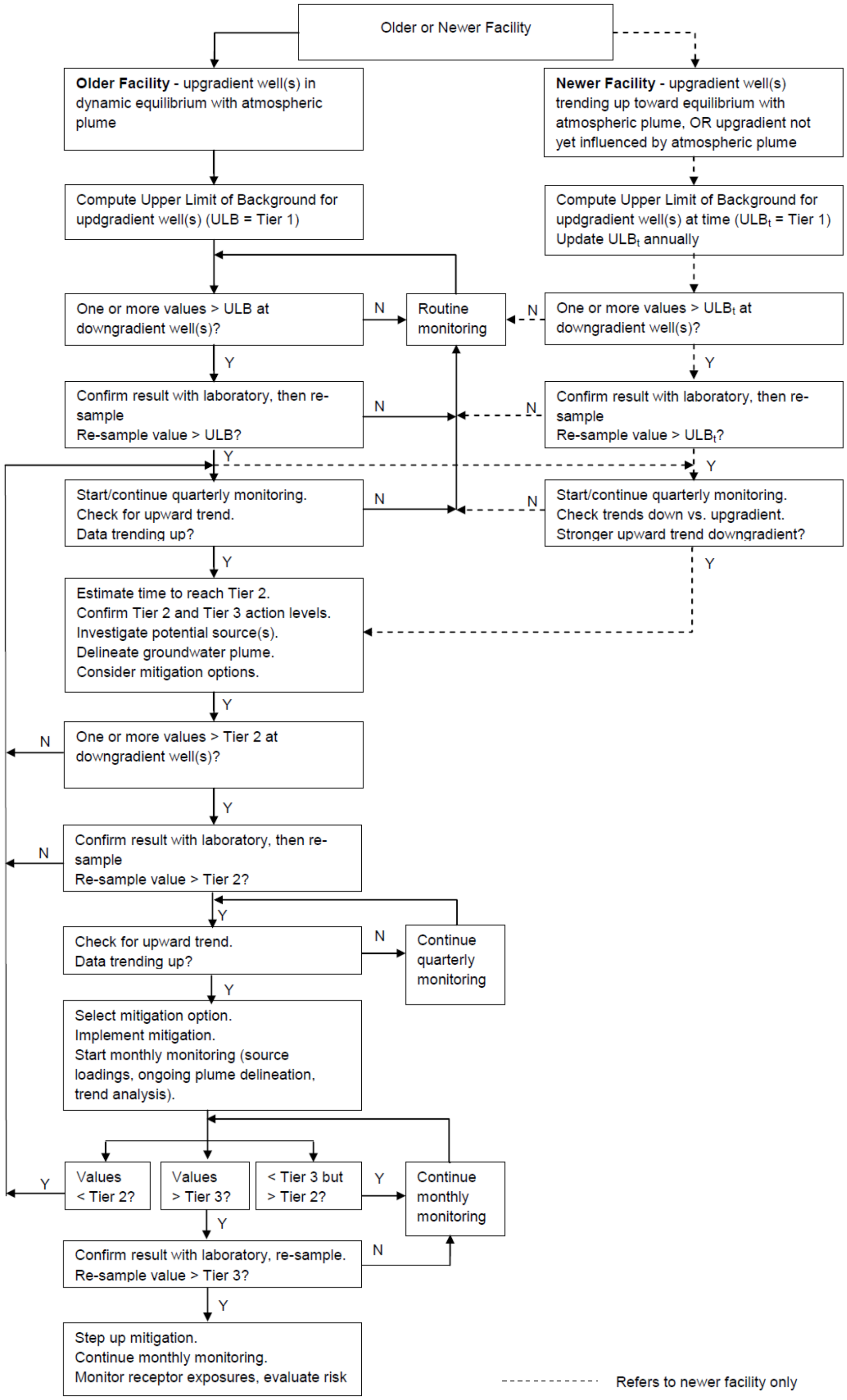

Figure 1 Decision Making Flowchart for Tiered Limits for Tritium in Groundwater

3.1 Tier 1 Administrative Level

The typical framework for estimating a Tier 1 administrative level (ULB) is based on determining if a point source of tritium contamination exists, as shown in Figure 2. This first step involves analysing existing groundwater monitoring data to determine if there is a systematic upward trend in tritium concentration in groundwater that would point to a potential point source. The methodology for estimating ULBs based on existing point source locations of tritium concentrations is discussed below. The methodology for estimating ULBs when a point source has not been identified is discussed in Section 3.1.5.

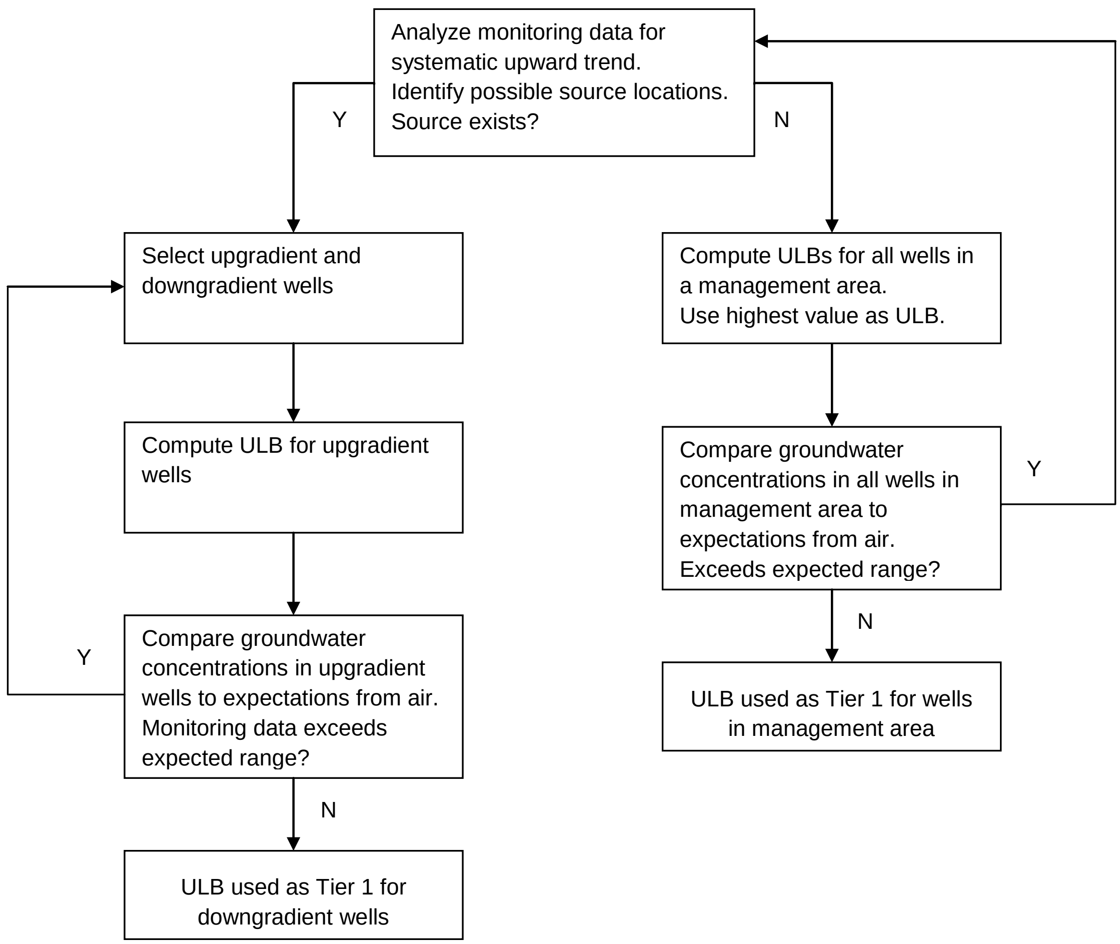

Figure 2 Flow Chart for Calculating ULBs with and without Point-Source

The Tier 1 administrative level represents an upper limit of background (ULB) for a monitoring location that is up-gradient of a potential source to groundwater, but not so far from the down-gradient monitoring well location as to have a substantially different atmospheric plume exposure. The down-gradient monitoring location will be down-gradient of the same point source, given a monitoring objective of recognizing any influence from the point source.

The selection of an up-gradient location may be complicated if groundwater flow is artificially influenced. For example, pumping up-gradient of the reactor building might reverse the natural groundwater flow direction. Professional judgement should be used to find a location, in the direction that is naturally up-gradient, that is not influenced by known subsurface leaks or other point sources such as reactor building roof drains.

The up-gradient well will often be influenced by the atmospheric plume. After the up-gradient location has been selected, a check should be performed to ensure the up-gradient well reflects the atmospheric plume and is not influenced by a subsurface source. The expected concentration (or range) of tritium in groundwater at the well screen depth, based on partitioning of tritium in air to surface soil water, and decay of tritium during vertical transport to the well screen, should be estimated. The CSA N288.1-08 [5] well model is appropriate for this purpose. The concentration of tritium in well water (X_{2w}) can be estimated as follows:

$$X_{2w} = X_{01} P_{13spw} P_{3spw2w} \qquad (1)$$

where,

X_{01} = the concentration of tritium in air (Bq/m^3)

P_{13spw} = the transfer parameter from air to soil pore water (equation 6-52 in [5]) (m^3/L)

P_{3spw2w} = the transfer parameter from soil pore water to well water (equation 6-47 in [5])

The average concentration of tritium in air at corresponding well locations can be evaluated through modelling the atmospheric plume according to CSA N288.1-08 [5], using facility emissions data and meteorological data. These results can be represented by a contour map.

If observed groundwater concentrations are consistent with the expected concentrations, then there is no evidence of influence by a sub-surface source and the up-gradient well is considered appropriate for estimating a ULB criterion.

3.1.1 Calculating ULB

A ULB (i.e. not influenced by abnormal leaks) can be defined easily for an up-gradient monitoring location if there is no systematic long-term temporal trend. A simple method is to calculate the mean plus 3 standard deviations, using existing data for the up-gradient well, or several wells if they are both considered representative. This value estimates the 99.9th percentile for a normal distribution. For data with an underlying log-normal distribution, the geometric mean will track the central peak of the distribution better than the arithmetic mean (i.e., the geometric mean will be less than the arithmetic mean) and the geometric standard deviation will provide a better measure of the spread of the distribution; however, the geometric mean should only be used when a large data set has been used to clearly demonstrate a log-normal distribution.

Since in most cases a large data set for the up-gradient well does not exist, the normal approximation described above is appropriate.

An Upper Limit of Background (ULB) can be defined as follows:

$$ULB = M + 3 * S \qquad (2)$$

where,

M = arithmetic mean of the data

S = standard deviation of the data.

The ULB criterion will be applied at a down-gradient location, with well depth similar to the up-gradient location. The up-gradient and down-gradient locations should not differ substantially in atmospheric tritium exposure. This will likely be the case if both are close to the potential source of release to groundwater. Both wells may be influenced by the atmospheric plume, but to a similar degree.

Any seasonality in the measured values will tend to increase the value of S and hence the ULB; however, attempting derivation of seasonal ULB values is not recommended. Seasonal variation should simply be considered part of the normal background condition.

If there is a systematic long-term trend in the measured up-gradient data, the ULB should be recalculated every few years to reflect the temporal trend. A decreasing trend might be evident, for example, if groundwater at the monitored depth is recovering from a pulse of tritium associated with historical weapons testing in the 1950s and early 1960s. A decreasing trend could also be evident if historical atmospheric releases from the facility were much higher.

If non-detects (reported as less than some critical level, L_C) are included in the data set but are not predominant, then for calculating descriptive statistics such as mean and standard deviation, non-detects are often replaced with a value of ½ L_C [6][7]. More detail on how to treat non-detects is included in COG-10-3069 [3] and CSA N288.4-10 [8].

3.1.2 Exceeding a ULB

The actions to be taken when a down-gradient well exceeds the ULB are primarily investigative. The first action would be to confirm the reported value with the laboratory. If confirmed, a second sample should be taken and analyzed to ensure that the result is reproducible. If so, it is appropriate to investigate temporal trends in the data. An increased monitoring frequency (e.g. quarterly) may be appropriate to facilitate trend detection. Monitoring frequency would be increased at both up-gradient and down-gradient wells. Depending on the period of record, several years of additional data may be needed to adequately evaluate trends and confirm whether concentrations are systematically increasing.

If an increasing trend is confirmed, the investigation would proceed to consider the expected timeframe to reach the Tier 2 level (Section 3.2), to confirm that the Tier 2 level leaves adequate time for mitigation, to confirm adequate conservatism in the Tier 3 level (Section 3.3) based on modeled plume attenuation between well and receptor, to identify potential sources and release mechanisms, to delineate the plume and assess potential risks, and to identify possible mitigation options. Mitigation options would be planned conceptually at this stage.

In the case of a legacy plume, where the source has already been eliminated, mitigation options would focus on plume management rather than source control.

If the Tier 2 or Tier 3 level is already clearly exceeded, this would be indicative of a historical issue rather than a newly emerging issue, and appropriate action should be taken as described in Section 3.2 (Tier 2) or Section 3.3 (Tier 3).

3.1.3 Evaluating a Trend

If there is a confirmed exceedance of the ULB at a monitoring well, the exceedance could be the result of random variation or seasonal fluctuation in the data, particularly if there is large uncertainty in the ULB due to small sample size. Therefore, the next investigative step is to increase monitoring frequency (if necessary) and then check for a systematic upward trend over a sufficient period of record. A sample size of at least 12, over a period of two or more years is recommended.

The Mann-Kendall test for trends is recommended [9]. This non-parametric test is not dependent on any underlying data distribution. Moreover, since it uses the sign of differences between measured values, non-detects may be replaced by any value that is less than the smallest measured value in the data set. If the data set is large (more than 40 data points) the normal approximation to the Mann-Kendall test may be used; otherwise, the standard test is recommended. The test should be performed as a one-sided test.

If a systematic upward trend is confirmed at a monitoring well, further investigation of the issue is warranted (Figure 1). If no trend is confirmed, it is appropriate to return to the routine monitoring frequency. The ULB should be recalculated using the full data set.

3.1.4 New Facilities

Older facilities have generally had the opportunity to collect groundwater data over an extended period of time compared to newer facilities, and there may be a better understanding of potential sources of tritium on site. A new facility should have some baseline data for the site that can provide a lower bound for the ULB; however, baseline data may not reflect any influence from the facility's atmospheric plume on groundwater. Depending on depth to water table, a decade of operation may be necessary for monitored groundwater to fully express this atmospheric influence and reach dynamic equilibrium.

For a reasonably constant atmospheric plume, the equilibrium concentration of tritium in groundwater at a specified depth may be estimated using the well model from CSA N288.1-08 [5]. As described in Section 3.1, this model incorporates partitioning from air to soil water, and decay over the period of vertical transport to the well screen. Default rates of vertical transport may be replaced with site-specific data, if available. The model can provide an early estimate of the future equilibrium groundwater condition at a monitoring location, before it has been realized. The timeframe needed to reach this equilibrium can be estimated from the vertical transport rate.

Using the estimated timeframe, Figure 3 presents an approximate trajectory for the well water concentration over time, based on default vertical transport rates. This will serve as a Tier 1 (ULB_t) value over the first few years while a database of monitoring data at up-gradient and down-gradient locations is obtained. Subsequently, when sufficient monitoring data are available, ULB_t can be derived from the measured up-gradient data. ULB_t should be updated annually.

After a few years of operation, a systematic upward trend in background should be seen. If such a trend is evident at the up-gradient well, then linear regression may be applied over the period of the upward trend to estimate the mean at time t (M_t), and the residual standard deviation (S_r). The ULB_t for a particular point in time (t) can then be estimated according to equation (2) in Section 3.1.1.

Since the residual standard deviation (S_r) represents variability around the trend line, it will not be inflated by the systematic trend in the data. When the groundwater data are no longer trending, a dynamic equilibrium with the atmospheric plume can be assumed, and the methods of Section 3.1 above are applicable.

The actions to be taken when a down-gradient well exceeds the ULB_t are primarily investigative, as described in Section 3.1.2. However, if the groundwater is still approaching its equilibrium with the atmospheric plume, the relevant question about trend is whether the down-gradient well shows a stronger increasing trend than the up-gradient, indicative of a non-atmospheric source contribution. Visual inspection of down-gradient and up-gradient data may be used to determine if there seems to be a stronger time trend down-gradient. If so, the hypothesis should be tested. Gilbert (1987) [9] gives a non-parametric test for comparing trends at two stations, based on the Mann-Kendall trend statistic at each station.

If an increasing trend is confirmed, the investigation would proceed to consider the expected timeframe to reach the Tier 2 level (Section 3.2), to confirm that the Tier 2 level leaves adequate time for mitigation, and to confirm adequate conservatism in the Tier 3 level (Section 3.3) based on modeled plume attenuation between well and receptor.

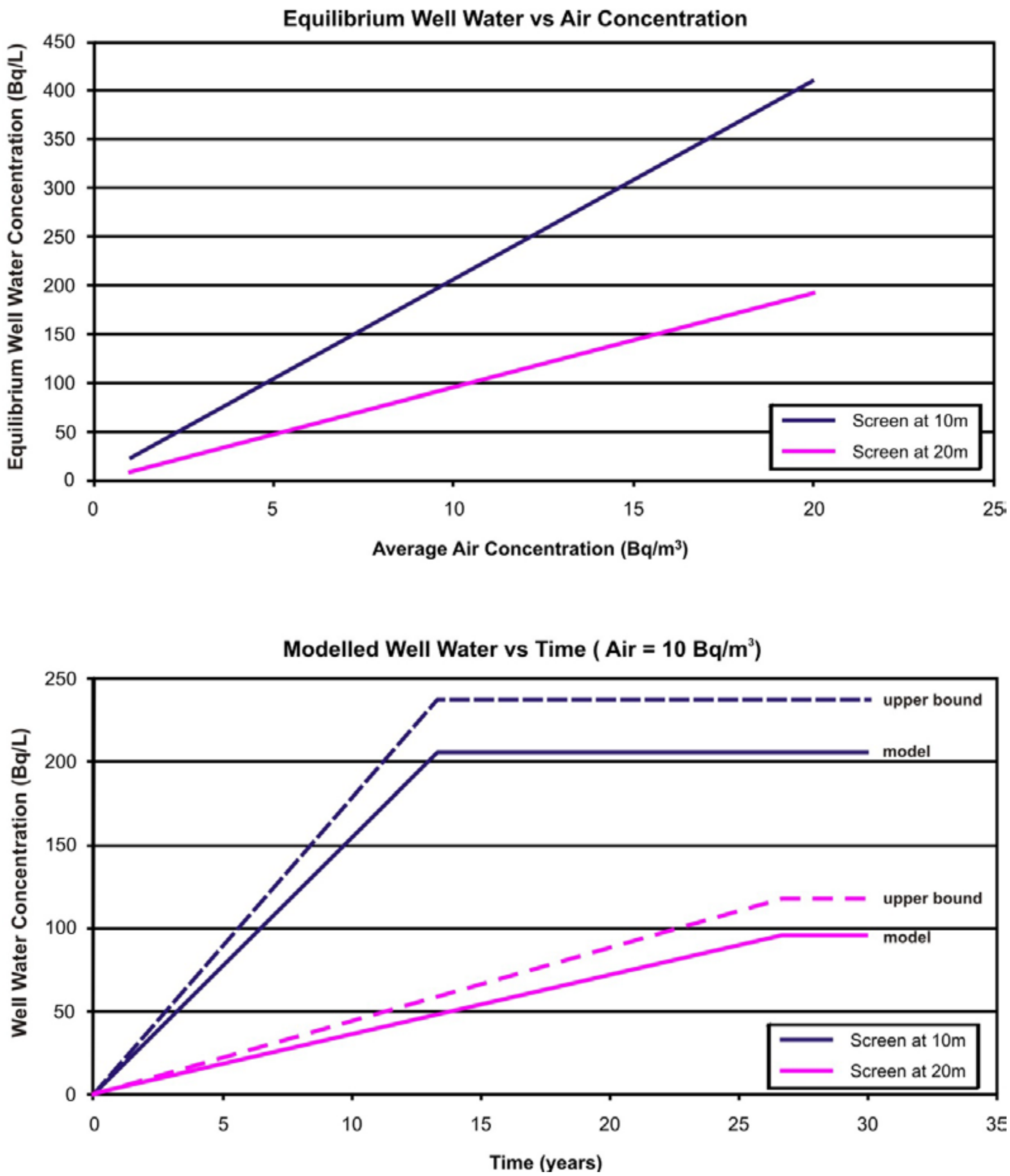

Figure 3 Modelling of Approach to Equilibrium of Tritium in Groundwater with Air over Time

3.1.5 No Apparent Source

Irrespective of the facility being categorized as old or new, a point-source may not be identifiable (see Figure 2). If a source cannot be identified but a potential future source is anticipated, an upward trend in existing groundwater monitoring data might indicate a potential leak to groundwater. Groundwater concentrations exceeding the range expected from the atmospheric plume would indicate a potential leak to groundwater. The CSA (2008) well model can be used to estimate the expected range of tritium in groundwater based on transfer from the atmospheric plume. If there is no apparent source, ULBs should be calculated for all wells in an identified management area (e.g. around the reactor building). As a generic Tier 1 level, the highest ULB in that management area should be selected. The generic Tier 1 level can be used until a source has been identified. At that point, an up-gradient well would be selected and used to calculate a more specific ULB.

3.2 Tier 2 Administrative Level

The Tier 2 level will be above the ULB, but below the Tier 3 level for the down-gradient well (see Section 3.3). In general, the Tier 2 level should be approximately 10% of the Tier 3 level; however, lower values may be needed depending on the mitigation options that were identified following confirmation of a trend above the Tier 1 level.

The action to be taken when a down-gradient well exceeds the Tier 2 level should be to first confirm the reported value with the laboratory. If confirmed, a second sample should be taken and analyzed to ensure that the result is reproducible, as per when Tier 1 is exceeded. The next step should be to check for an increasing trend and, if confirmed, to implement mitigation that can be expected to prevent exceedance of the Tier 3 level. Mitigation could include curtailing a leak to groundwater or installing a collection system to capture contaminated groundwater near the source, as examples. Subsequent monitoring should be more frequent (e.g. monthly) and designed to confirm that the mitigative action is succeeding.

In the case of a legacy plume, where the source has already been eliminated, it is possible that Tier 2 levels are exceeded and that Tier 3 levels clearly will not be exceeded. If this can be demonstrated, then monitoring of natural attenuation may be an adequate action. If this cannot be demonstrated, then plume management action will be needed. Similarly, if Tier 2 levels are exceeded in a down-gradient well as a result of infiltration from reactor building roof drains, and if it can be demonstrated that Tier 3 levels will not be exceeded, then continued monitoring may be adequate action. If it cannot be demonstrated that Tier 3 levels will not be exceeded, then mitigation is appropriate to prevent Tier 3 exceedance.

3.3 Tier 3 Administrative Level

The purpose of having Tier 1 and Tier 2 levels is to ensure that the Tier 3 level will not be exceeded. Appropriate mitigative action should be initiated when Tier 2 levels are exceeded. If these actions are implemented correctly/successfully, Tier 3 should not be exceeded.

The action to be taken when a down-gradient well exceeds the Tier 3 level and re-sampling confirms this exceedance should be to step up or implement further mitigation measures to ensure that harmful concentrations do not reach the receiving water body. Additional actions to those taken at the Tier 2 level would be expected.

The Tier 3 level should be set at or below the lowest of the Risk-Based Concentrations (RBCs) for groundwater at the monitoring well location. The RBC is a receptor-specific value that is considered to be protective of the receptor, when met at the well location. For a groundwater plume on site, the down-gradient receptors would typically include aquatic invertebrates living in or on the substrate of the down-gradient surface waters. Potentially, they could be terrestrial plants growing near the shore, with roots near the water table and exposed to groundwater as a result of water table fluctuations, or soil invertebrates living near the shore exposed to water table fluctuations or groundwater seepage. These are organisms with small home ranges that could be expected to spend most of their lives in the zone of groundwater discharge.

Relevant receptors could also include humans using drinking water that is subject to influence from down-gradient surface water, such as a nearby water supply plant or a cottage on the shoreline. These drinking water intakes would be farther away, beyond the zone of groundwater discharge.

When mitigation appears to be succeeding, with a demonstrated downward trend, monitoring frequency might be reduced again based on a good understanding of the groundwater plume and a clear expectation of returning to tritium concentrations below the Tier 3 level.

3.3.1 Generic RBC

The derivation of RBC levels for ecological and human health protection is presented in COG-10-3069 [3]. A summary of the methodology used is described below. Ecological RBCs were estimated for aquatic and terrestrial organisms. For aquatic organisms the RBC was based on a water quality criterion, adjusted to account for the attenuation of tritium along the groundwater path to surface water, and dilution of groundwater in surface water. For terrestrial organisms the RBC was based on a groundwater criterion for a point beneath the organism's soil exposure zone. These values were estimated based on conservative assumptions regarding dose benchmarks. Tritium water quality criteria for aquatic and terrestrial organisms were derived from dose benchmarks from both UNSCEAR (1996) [10] and Environment Canada/Health Canada (2003) [11], and using a relative biological effectiveness of 3.

The human health RBC was based on the Health Canada drinking water criterion (7,000 Bq/L), increased to account for attenuation of tritium along the groundwater path to surface water, and dilution of groundwater in surface water between the site and a drinking water intake from the surface water body. This criterion was modified because there are no known drinking water supply wells down-gradient of nuclear power stations in Canada.

The lowest of the ecological and human health protection values was selected and an additional 10-fold safety factor was applied, producing a default conservative Tier 3 level of $3x10^6$ Bq/L that could be appropriate for all facilities. This value is significantly different than the CNSC's recommended design objective for tritium in groundwater of 100 Bq/L for new nuclear facilities. This design objective is not risk-based, but rather is reflective of what is considered technologically and economically achievable [12].

Where site-specific data are available, it would be appropriate to calculate a more realistic Tier 3 RBC level for any given monitoring well. Site-specific Tier 3 levels would be expected to be of a similar order of magnitude as the generic Tier 3 level.

4. References

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