Mine Closure 2023 - Behrooz Abbasi, Jeff Parshley, Andy Fourie & Mark Tibbett (eds)
© 2023 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-7-2
doi:10.36487/ACG_repo/2315_090

A framework for managing contaminants at legacy mine sites

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Abstract

Contaminant management at legacy and abandoned mines can be a complex and lengthy process, and often involves the management of more than one type of contaminant and contaminant source. This can be compounded by naturally occurring contaminants (e.g. metals, nutrients) in certain sedimentary rock formations that may be associated with coal, phosphate, uranium, or metals resources. Exposure of this rock and its placement as waste rock during mining can enhance the release of naturally derived "contaminants" through operations, closure, and reclamation. Upon entering receiving environment areas, the interaction between certain contaminants and receiving waters can enhance transformation into more biologically available forms that may be taken up more readily into the aquatic food chain. For mines that have already stopped operating, addressing risks associated with the ongoing release of bioavailable contaminants can be challenging. Legacy and abandoned mines can benefit from a site-specific management plan that characterises how contaminants move on the site and in the environment, and outlines and evaluates best achievable alternatives to mitigate the potential for effects.

We developed an adaptive framework that outlines the relationship among effects linkages from sources, transport pathways, and aquatic receptors, and site-specific factors influencing contaminant fate and transport such as geochemical processes and water management. The framework is a tool that can be used to develop a pollution prevention hierarchy that prioritises source control followed by water management and treatment approaches, and potential mitigation activities with short- and long-term application, including site characterisation and monitoring needs. The use of this framework allows for a methodical and streamlined review of available site information, identification and filling of data gaps, and identification and evaluation of mitigation options that will complement closure activities. This paper will describe the development of the plan framework and its' application to address a variety of challenging contaminant management issues.

Keywords: *abandoned mine, adaptive framework, contaminant management, effects linkages, legacy mine, pollution prevention hierarchy, monitoring, site characterisation*

1 Introduction

As the mining industry's knowledge of environmental contamination increases, and as regulatory requirements for mine closure continue to advance, so too does the need for a variety of tools that effectively support management of environmental liabilities at legacy and abandoned mine sites. Though there are a multitude of resources currently available to approach mine closure issues, this paper is intended to provide practitioners with a supplementary tool to think through a contaminant management problem: a framework that provides a methodical approach for addressing contaminant management challenges at legacy and abandoned mine sites. The framework can be used to outline the relationship among effects linkages from sources of contamination, transport pathways, and human and/or ecological receptors, and site-specific factors that influence contaminant fate and transport.

Contaminant management at legacy and abandoned mines is an issue that persists globally and has been the subject of several international forums and workshops. The first international workshop on abandoned mines was held as early as 2001, in Santiago, Chile, during which several environmental contamination issues were identified (Chilean Copper Commission and United Nations Environment Programme 2001). Since that time, mining companies and government agencies have both developed programs to better manage environmental liabilities at mine sites located on public and/or private lands. Moreover, the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF) surveyed member countries across North America, Europe, Africa, Asia, and Oceania between 2019 and 2020 to assess current policies, regulations, and practices related to mine closure. While most countries surveyed indicated that they had legal requirement(s) to submit a mine closure plan as part of mine development, the level of detail required in these plans varied widely (Stevens 2021). In North America, state and provincial government departments in the United States and Canada, respectively, have developed programs that use risk-ranking methodologies to help prioritise higher risk sites for action to manage the clean-up of abandoned mines (Nevada Division of Environmental Protection 2023; BC Ministry of Forests 2020). Mining companies around the world have also developed initiatives to resolve insufficient closure activities at sites that were historically 'closed'.

These developments are positive; however, where historical mining activities were conducted in the absence of closure requirements or where implementation of closure activities did not meet present-day best practices and/or regulations related to mine closure, mines can be faced with ongoing contaminant issues that present risks to human health and the environment. The associated financial and legal aspects of contaminant management are also challenging to adequately define, especially in the context of abandoned mines, where a responsible party may be difficult to identify. Furthermore, legacy and abandoned mines are typically each faced with a unique set of environmental, social, economic, and technical issues such that an over-arching approach to closing these types of sites is not considered practicable.

The contaminant management framework is a tool that can be used to help resolve some of these technically and financially challenging factors. The tool is adaptive and can be used to develop a site-specific management plan that characterises how contaminants move on the site and in the environment, and outlines and evaluates best achievable alternatives to mitigate the potential for effects. It allows for methodical and streamlined review of available site information, identification and filling of data gaps, and identification and evaluation of mitigation options that can complement closure activities.

2 The contaminant management framework

The framework is rooted in the source – pathway – receptor (S-P-R) model, which is a commonly used concept to inform decision-making related to contaminant management at both small and complex contaminated sites. The S-P-R model describes the source(s) of contaminant(s), transport pathway(s) from a source to the receiving environment, and mechanisms by which contaminant(s) are taken up by receptor(s) in the receiving environment.

A simplified S-P-R model is illustrated on Figure 1. In this example, the S-P-R model for a legacy mine could be described as follows:

1. A waste rock pile, containing elevated concentrations of metals parameters, was constructed during historical operations of a mine; the waste rock pile was not covered upon closure of the mine. The waste rock pile acts as a *source* of contamination.
2. Precipitation and/or infiltration can entrain metals into water conveyance structures such as drainage ditches, or small tributaries. The surface water acts as a *transport pathway* from the source of contamination to a receiving environment.
3. Surface water discharges into a receiving environment, such as a fish-bearing stream or lake. Organisms within the receiving environment (e.g. aquatic invertebrates, fish) are potential *receptors* of contaminants. Elevated concentrations of some metals and other contaminants can pose health risks to receptors.

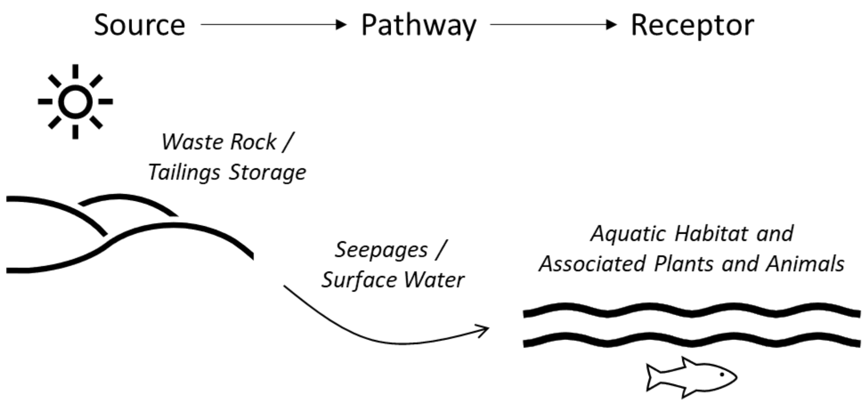

Figure 1 Source-pathway-receptor (S-P-R) concept

With the S-P-R model as its foundation, the overall framework, as illustrated in Figure 2, is constructed through the addition of several more components, such as:

- effects linkages,
- influencing factors,
- site characterisation and confirmatory monitoring, and
- management activities.

The framework informs the development of site-specific management plans, which are intended to be living documents and updated as new information becomes available and provide decision criteria to support sound and timely decision-making regarding contaminant management.

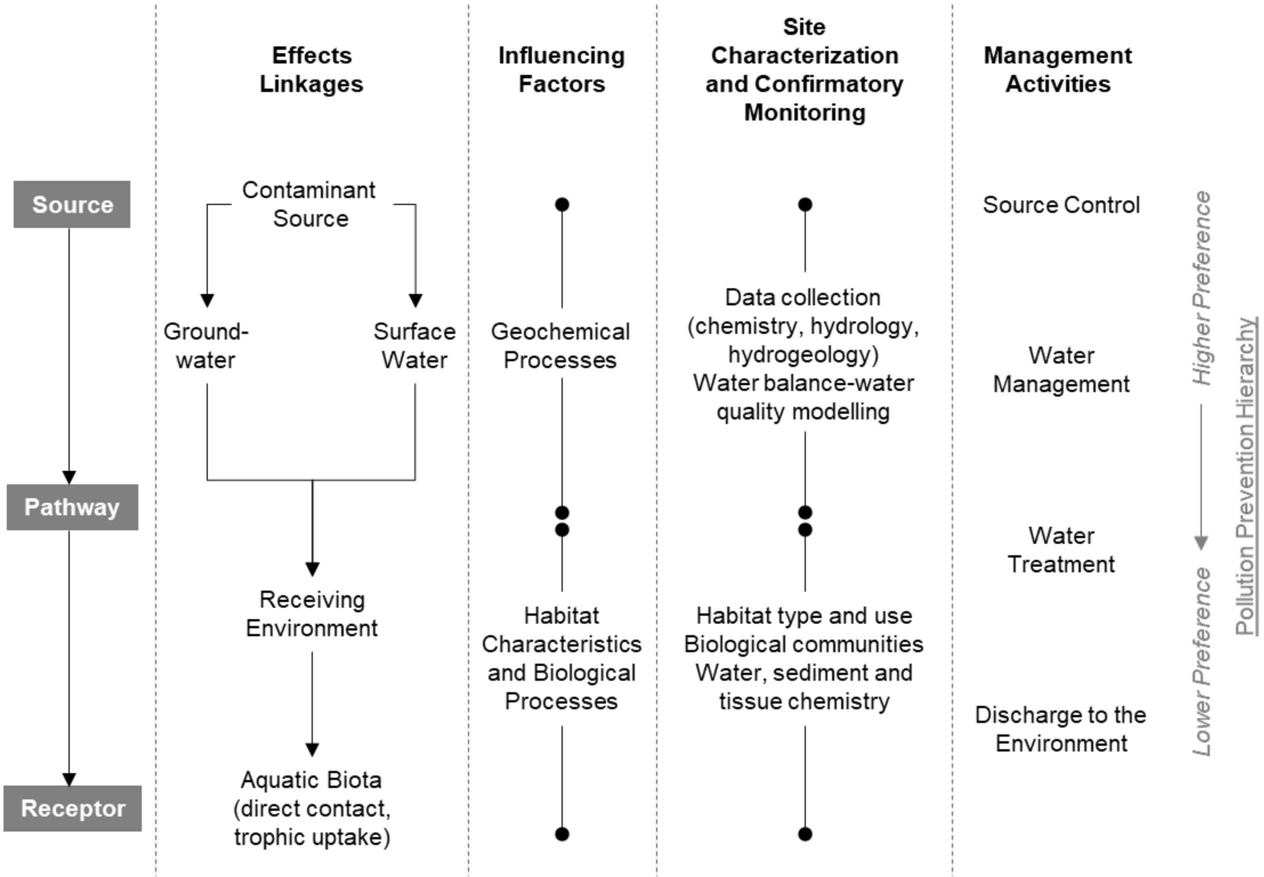

Figure 2 An illustration of the contaminant management framework approach

As part of the framework, data collected from each individual component is integrated to develop a conceptual site model (CSM). Development of a preliminary S-P-R model provides the basis for identifying potential effects linkages and development of characterisation programs. As site characterisation data are collected and interpreted, influencing factors become better understood, and effects linkages are confirmed. As effects linkages are confirmed, additional characterisation studies may be developed (e.g. biological studies to assess potential exposure of receptors to contaminants) in order to evaluate the potential need for management activities. As this iterative process continues, decision-making regarding management activities becomes increasingly more effective.

The framework is also applicable after a management activity has been selected and implemented. With the S-P-R model continuing to serve as the foundation of the framework, confirmatory monitoring programs are developed to evaluate the effectiveness of selected management activities. The results of these programs are in turn used to determine if a management activity is performing according to its intended objective. Where activities are not meeting intended objectives, effects linkages and/or influencing factors may be revisited to assess if conditions have changed or determine if other factors may be contributing to observed outcomes.

This overall process – from development of a preliminary S-P-R model through to selection and monitoring of management activities – creates an adaptive approach to contaminant management. An advantage to this approach is that once the available data and information are compiled, it becomes easier to identify gaps in the existing dataset and the CSM. As the CSM becomes further advanced, modifications or refinements can be made to selected management activities and/or monitoring programs.

Finally, the framework is intended to act as a tool that encourages mine closure practitioners to thoughtfully reflect on data collection needs in a manner that is aligned with overall closure objectives for a mine.

Considerations for, and examples of each of, the framework components are described further in the following sections.

2.1 Effects linkages

Effects linkages are the pathways that link sources of contaminants with receptors in a receiving environment. Effects linkages generally consist of two components:

1. the physical processes at a site that move a contaminant from its source into a transport pathway and subsequently to a receiving environment. Examples of physical processes are: groundwater discharge to a creek; surface water runoff from a waste rock pile or tailings area; seepage from a waste rock pile or a portal; aerial deposition of dust to surface water.
2. the effects of direct exposure to a contaminant, such as through water contact, or indirect exposure, such as through diet.

2.2 Influencing factors

Interpretation of effects linkages between contaminant sources, pathways, and receptors requires a robust understanding of influencing factors, which are often unique to a given site. Influencing factors are site-specific conditions and processes that affect the fate and transport of contaminants moving from source(s) to receptor(s). Influencing factors can affect how contaminants are released from a source, change how contaminants move at a site, and alter the potential of a contaminant to cause effects to a receptor in a receiving environment. Examples of influencing factors are as follows:

- site-specific mineralogy, both locally and regionally (e.g. presence of naturally occurring contaminants)
- volume of reactive vs. neutralising materials
- fault lines that provide preferential pathways and/or physical barriers to groundwater flow

- potential for adsorption and desorption of contaminants along groundwater pathways
- conditions that cause speciation of contaminants to more bioavailable forms
- water flows (e.g. stagnant and reducing vs. flowing and well-oxygenated)
- degree of vegetation in the receiving environment and associated trace metals uptake or sequestration

Understanding site-specific influencing factors and how they may or may not affect how contaminants can cause effects to receptors in the receiving environment has implications to the identification and selection of appropriate management options.

2.3 Site characterisation and confirmatory monitoring

Site characterisation and confirmatory monitoring programs are developed and implemented to identify and confirm the effects linkages and influencing factors for a mine site, and to provide information to evaluate the effectiveness, or need for refinement, of management activities. Ideally, at least some information would already be available to provide the basis for understanding data gaps and designing contemporary sampling programs. However, for older mines, records may not have been kept, or may not have been maintained after operations ceased. Data quality and compatibility with contemporary analytical methods or regulatory requirements may be of concern where data are available.

Following review of historical records and determination if they are suitable for use in site characterisation and confirmatory monitoring, additional sampling is likely to be needed. The scope of the sampling program(s) will need to take into consideration factors such as:

- Site size and location – mine sites often extend across a large footprint with multiple discharge points (e.g., seepages and portals) and may also cover several sub-areas that have different biogeoclimatic conditions or proximity to human uses. As well, access may be constrained where roads have been decommissioned or not maintained, requiring alternative means of access.
- Suitable media – depending on the type of contamination and exposure pathways, multiple or tiered sampling programs may be needed to obtain media such as soil, surface water, sediment, tissues, and biological community structure to appropriately assess the level of risk associated with residual contaminants. The assessment of risks will also need to take into consideration the protection objectives for the contaminant management, for example subsistence consumption of fish by humans or maintenance of a species or population at risk.
- Natural variability – sampling will likely need to be conducted at both reference and exposure sites across an annual hydrological cycle or even multiple years to develop an understanding of how changes in flows and seasons influence the site's water balance, contaminant concentrations, and transport pathways. Biological communities can also change naturally due to interannual variability in weather, and increasingly, climate change.
- Volume of contaminated material – mine wastes (e.g. tailings, waste rock) are often present in large quantities that are not practicable to fully characterise using traditional approaches. For example, one tailings impoundment at the former Anaconda Mine near Butte, Montana extends over more than 1,000 acres (approximately 4,047 m^2) and ranges in depth up to 100 feet (approximately 30 m) (United States Environmental Protection Agency 2000). Thoughtful, scientifically based approaches to sampling and characterising large volumes of material may be required.

Without a methodological approach to site characterisation and monitoring, the associated costs can increase rapidly and desired timelines to achieve closure objectives can quickly be extended. The framework can help guide study design as it promotes thinking about a subject site from the perspective of the S-P-R model and in the context of effects linkages and influencing factors. For example, one of the most important components of site characterisation is the water balance of the site. Hydrological and hydrogeological process are key transport pathways to receiving environments and represent opportunities for source control or other higher priority mitigations.

2.4 Management activities

Management activities fall into several general categories (e.g. institutional controls, engineering controls, etc.) and within each category are numerous specific actions that can be combined. At the outset, potential mitigations should be considered within a pollution prevention hierarchy, which is an ‘order of preference’ or a ‘priority list’ for addressing pollution, such as contamination from legacy mines. The preference is to first take action(s) at the highest level of the hierarchy because higher level actions can eliminate or reduce the need for actions at lower levels.

The pollution prevention hierarchy informs national and provincial/state laws in Canada and the United States, as well as in other countries globally. For example, the Government of Canada (Canada) defines pollution prevention as *“… the use of processes, practices, materials, projects, substances or forms of energy that avoid or minimize the creation of pollutants and waste, and reduce the overall risk to the environment or human health*” (Government of Canada 2023). The United States *Pollution Prevention Act* establishes a similar hierarchy: “…*pollution should be prevented or reduced at the source whenever feasible; … and disposal or other release into the employed only as a last resort and should be conducted in an environmentally safe manner”* (United States Environmental Protection Agency 2023).

The first preference should be to prevent contaminant release at the outset and thus eliminate the potential for contaminants to reach a receiving environment. When prevention is not possible, other actions (e.g. mitigation options) will need to be considered. Regardless of the selected action(s), the goal is to achieve contaminant concentrations that are protective of receiving environment uses.

In the context of legacy and abandoned mine sites, the contaminant management framework outlines the pollution prevention hierarchy as follows:

1. Source control
2. Water management
3. Treatment
4. Discharge to the environment

Although the highest preference within the pollution prevention hierarchy, source control measures can be difficult to implement at legacy and abandoned mines. For many sites that exist today, control at source may not be possible; for example, where waste rock storage is extensive, and it is not physically practicable or economically feasible to import sufficient material for covers. In such case, other actions (e.g. water management, treatment, and/or discharge) may be required.

Some of the opportunities and challenges associated with the pollution prevention hierarchy at legacy and abandoned mine sites are presented in Table 1.

Table 1 Opportunities and challenges associated with source control, water management, treatment, and discharge at legacy mines

Management approach	Opportunities	Challenges
Source control	• Provides a more definitive solution to associated legal and financial liability • Traditionally the preferred approach for Indigenous communities	• Availability of adequate cover material • Economically not practicable due to volumes of waste materials • Relocation of waste materials can result in re-mobilisation of contaminants at a new point location(s)
Water management	• Supporting infrastructure from mine operations can be re-purposed for water management during closure • Can be used to minimise the volume of water requiring treatment or disposal (e.g. clean water diversions) • Passive methods can be implemented	• Active systems may require ongoing maintenance and inspections, thereby increasing costs • May require a large physical footprint • Climate change and associated uncertainty
Treatment	• Supporting infrastructure from mine operations can be re-purposed for water management during closure • Numerous proven technologies available • Passive technologies can be implemented	• Active treatment requires manual oversight, thereby increasing costs • Depending on the selected technology, treatment can generate additional waste (e.g. sludge) that will require disposal
Discharge to the environment	• Reduces off-site disposal costs • Reduces off-site disposal volumes	• May still require treatment • Permits, and associated monitoring, may be required in the long-term • Requires a suitable discharge location • May not be preferable to local communities in the long-term

As with mine closure planning in general, an important aspect of management activities is defining objectives and success criteria to evaluate the effectiveness of the implemented actions. These objectives and success criteria need to be linked to the confirmatory monitoring program such that suitable data for evaluating success is obtained.

3 Application of the framework

The contaminant management framework can be applied at both surface and underground mine sites and for various types of contaminants associated with base metal, precious metal, and non-metallic (e.g. coal) resources. Regardless of the type of mine, the overall objective of the framework is to facilitate methodical and streamlined collection of data and information, identification and resolution of data gaps, and identification of site-specific management activities (as applicable).

Given the adaptive and iterative nature of the tool, the framework can be applied at any stage of the overall closure process – from initial characterisation and data collection efforts, through to effectiveness evaluation of management activities that have been implemented. At its core, the framework is intended to act as a tool that promotes thoughtful consideration of data collection needs, in a manner that is aligned with overall closure objectives for a mine. Examples of scenarios in which the framework can be applied to inform contaminant management issues are briefly described below.

3.1 Development of characterisation programs in the absence of historical information

One of the challenges with contaminant management at legacy and abandoned mine sites can be a lack of (or absence of) historical operational and/or baseline information: segregation of potentially acid-generating (PAG) and non-PAG waste rock may not have been tracked; the presence or absence of habitat and receptors in receiving environments adjacent to a mine may not have been assessed; baseline characterisation of soil and/or water quality, including background or reference concentrations, may not have been conducted. In the absence of adequate historical information, it can be difficult to identify a starting point for effective contaminant management at a site.

In such scenarios, the foundation of the framework – the S-P-R model – can provide the starting point, by facilitating identification of contaminant sources through, for example, initial reconnaissance or desktop reviews. The individual components of the framework (i.e. effects linkages, influencing factors, and site characterisation) subsequently provide the basis for a systematic approach to understanding variables that may not be readily discernible, such as transport pathways and potential receptors. Logically working through each component of the framework in a stepwise manner can provide answers to many of the key questions that need to be addressed to resolve contaminant issues, questions such as:

- What are the watercourses that hydraulically connect source areas to receiving environment(s)?
- What is the receiving environment, and does it provide habitat for receptors?
- Are receptors present within the receiving environment?
- Are exposure pathways present?

Once initial characterisation data have been collected, the findings can be used to refine next steps and subsequent stages of assessment.

3.2 Simplifying large, complex sites to streamline data collection

Application of the contaminant management framework can also be helpful way to simplify large, complex mine sites into several smaller, more manageable areas. For example, at mine sites covering large surface areas (e.g. hundreds of hectares) over multiple drainage basins, the framework can be used to sub-divide the overall mine footprint into smaller study areas or units, with the development of 'area specific' CSMs and focused studies being developed for each study area or catchment.

Once environmental conditions are established within each of the study areas or catchments, the relative risks between each of the areas can be ranked to identify areas of greater environmental concern, prioritise subsequent stages of characterisation or planning for management activities, and identify areas of a site where mitigation measures have the highest likelihood of yielding benefits to the environment.

3.3 Informing and prioritising timelines for management activities

Many legacy and abandoned mine sites, particularly in Canada and the United States, are located in remote areas and/or faced with seasonal access restrictions due to weather conditions. This results in a limited time period to carry out field studies and construction activities, which can present practitioners with dilemmas as to where and how to prioritise resources. The relationship between the site characterisation/confirmatory monitoring and management activities components of the framework can provide the basis for development of timelines for implementation of studies or potential mitigation measures.

Methodically working through the steps of the pollution prevention hierarchy alongside the site characterisation component of the framework can help identify activities that are 'design-ready' versus those that require further studies to be refined. This exercise informs the level of effort needed to implement various activities and identifies studies or activities that can be realistically implemented within available timeframes.

For example, an evaluation of source control measures may conclude that the types of management activities that are likely to have the greatest impact (i.e., result in the greatest reduction of contaminant release) require a longer time horizon to develop, due perhaps to a higher degree of uncertainty, unknown likelihood of success, or the need for extensive studies to define a path forward. This outcome can support decision-making to advance to the evaluation of management activities that may be of lower preference within the pollution prevention hierarchy (e.g., water management) but can be implemented within shorter timeframes. That is, the framework can help identify 'short-term' vs. 'long-term' management actions.

3.4 Evaluating the effectiveness of management activities

The framework can also be used to establish decision-making criteria, or success criteria, to evaluate the effectiveness of management activities and decisions. This is an important aspect of confirmatory monitoring and closure planning, with the need to confirm that closure goals are met. Because the framework is routed in the S-P-R model, the framework makes it easier to identify key metrics that are indicative of success. For example, success criteria can be defined based on reduction of contaminant concentrations (i.e. evidence of effective source control), removal or absence of surface water runoff conduits (i.e. evidence of successful water management efforts), or improvements in biological community metrics (i.e. evidence of increasing abundance or diversity in a receptor group).

4 Conclusion

Contaminant management at legacy and abandoned mines is an issue that persists globally. Where historical mining activities have been conducted in the absence of closure requirements or implementation of closure activities did not meet present-day best practices and/or regulations, mines can be faced with ongoing contaminant issues that present risks to human health and the environment.

To address challenges associated with environmental liabilities at legacy and abandoned mine sites, a variety of tools are needed. A contaminant management framework is one such tool which provides a methodical approach for addressing contaminant management at legacy and abandoned mine sites. The framework is rooted in the source – pathway – receptor (S-P-R) model, which describes the source(s) of contaminant(s), transport pathway(s) from a source to the receiving environment, and mechanisms by which contaminant(s) are taken up by receptor(s) in the receiving environment.

The tool is adaptive and can be used to develop a site-specific management plan that allows for methodical and streamlined review of available site information, identification and filling of data gaps, and identification and evaluation of mitigation options that can complement closure activities. The framework can be applied to inform a variety of contaminant management issues. At its core, the framework is intended to act as a tool that promotes thoughtful consideration of data collection needs and management approaches, in a manner that is aligned with overall closure objectives for legacy and abandoned mine sites.

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