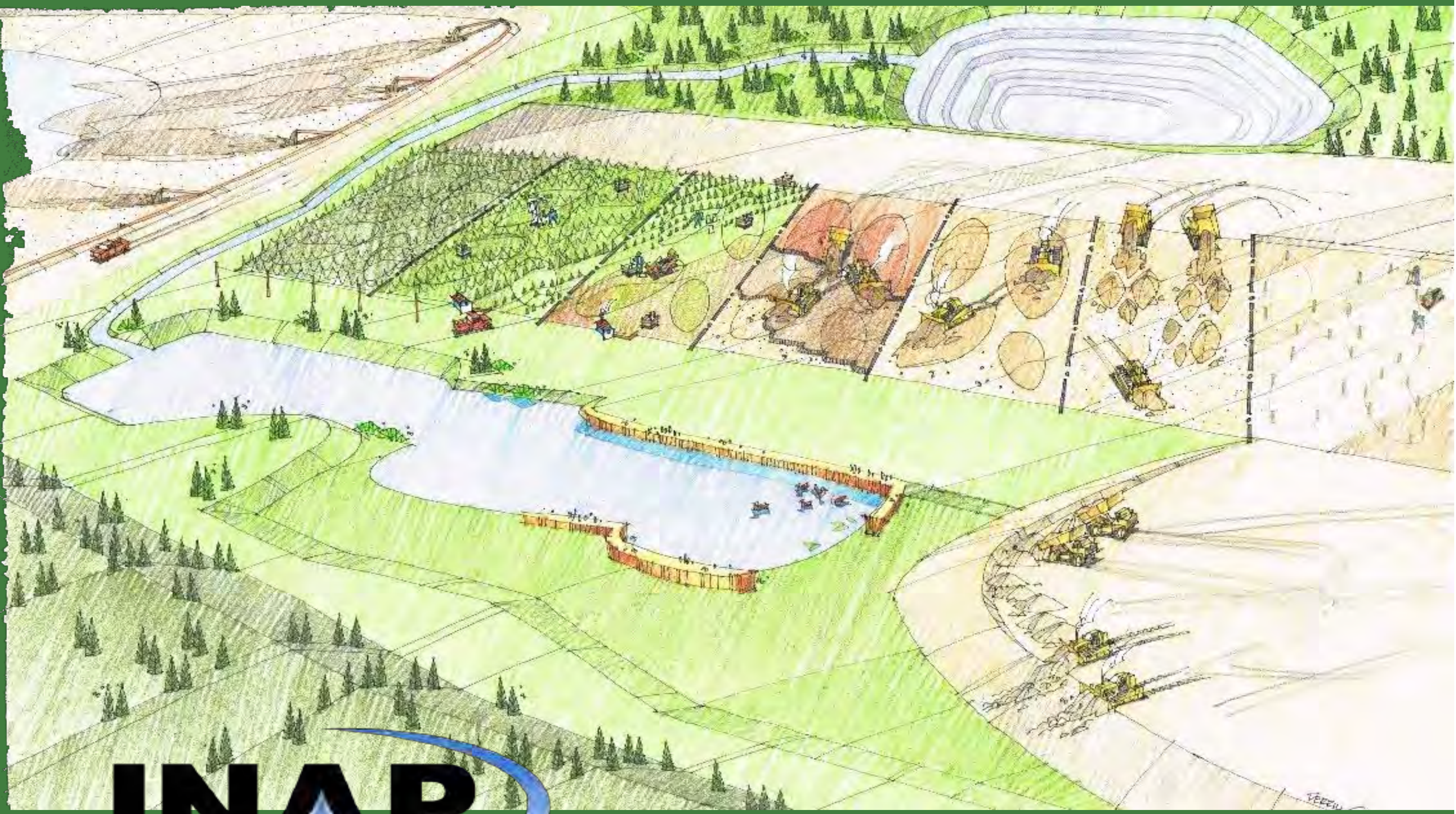
GLOBAL
COVER SYSTEM
DESIGN

TECHNICAL GUIDANCE DOCUMENT



INAP International Network for Acid Prevention

November 2017

EXECUTIVE SUMMARY

This document builds on previous technical guidance documents on cover system design, construction, and performance monitoring. This Global Cover System Guidance Document, like the GARD Guide, is intended as a best practice summary to assist mine operators, designers, and regulators to address issues where cover systems can be employed. The Global Cover System Guidance Document will be of interest to individuals who are seeking more detailed information than what is outlined in Section 6.6.6 of the *GARD Guide,* “Engineered Barriers”.

The Global Cover System Guidance Document is a technical document designed primarily for those investigating the use of cover systems on their mine sites. The underlying science and technology of cover system design is discussed in sufficient detail that the reader can understand the process of cover system design and monitoring. The guidance is meant to be followed in chronological order beginning from the early pre-feasibility stages of a project.

A holistic framework for management of reactive materials during operations and at closure is the pillar of the document. The framework for cover system design is presented at a high level, suitable for readers with minimal technical background. It is presented at a conceptual level, using a hierarchy of climate, geology and materials, and topography, leading to an understanding of the patterns of water movement on a specific landscape. Ultimately, these elements will govern how cover systems perform, and it is up to designers to manipulate them to achieve desired performance.

This document presents a conceptual model of how cover system designs might affect contaminant and acidity loading. This model attempts to determine when the varying roles of the cover system design (e.g., control of net percolation or oxygen ingress), might influence loadings. Acknowledgment of these unique relationships provides an opportunity to optimize ML/ARD management in a cost-effective manner. Other key concepts discussed within the document are the role cover systems play over the life of the mine from early conceptualization to long-term performance monitoring considerations.

Application of the holistic framework is achieved through the use of a cover system design tool that walks users through relevant climatic factors to optimize cover system design alternatives for a desired performance design criteria. This allows users to understand what a realistic objective is when developing cover system design alternatives based on site-specific climate conditions. Additionally, the tool refers to specific elements integral to the design where an in text commentary is provided. The tool helps identify where potential for management exists on the site, leading to the selection of the most appropriate form of prevention.

The information provided within the tool is not a replacement for site-specific classification and engineering required for cover system design. However, the tool is a means of beginning early conceptualization to help focus further investigation at a site level and to begin to form realistic expectations for cover system performance at an early stage of a project.

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1 INTRODUCTION

This Global Cover System Guidance Document, like the *Global Acid Rock Drainage Guide (GARD Guide)*, is intended as a best practice summary to assist mine operators, practitioners, and regulators to address issues where cover systems can be employed. The Global Cover System Guidance Document will be of interest to the same groups of individuals outlined in Section 1.1 of the *GARD Guide*.

The Global Cover System Guidance Document, from a technical perspective, is designed primarily for a scientist or engineer with a reasonable background in chemistry and the basics of engineering whom is tasked with the closure of a waste storage facility (WSF), although with minimal specific knowledge of cover system design. The underlying science and technology of cover system design is discussed in sufficient detail that the reader can understand how to design, construct and monitor a cover system, but the discussion stops short of being a formal scientific dissertation on the relevant aspects of, for example, geochemical kinetics and solute transport hydrodynamics. Rather, the document guides the reader through the logical framework of cover system design for WSF closure, and the potential for management that exists on the site, leading to the selection of the most appropriate form of prevention (as defined within the *GARD Guide*).

1.1 Context

Mining is a global industry, and the main wastes and by-products it generates are subject to the full range of climatic conditions found on earth. Proper management of waste material is required to manage risk(s) results from potential degradation of water quality, and limit environmental, social and financial liabilities. Managing mine wastes, whether in tailings storage facilities (TSFs), waste rock dumps (WRDs) or heap leach piles (HLPs), requires an understanding of how interactions with the local climate will affect weathering (oxidation) and leaching (net percolation), which in turn control the potential impact of waste material on the receiving environment. Cover systems are an essential component of modern mine waste management. The design, construction, performance, and monitoring of these systems is the topic of this guidance document.

The majority of chemically reactive mine waste is associated with sulphide oxidation and the concomitant release of constituents of potential concern. In Australia and Southeast Asia, the mining industry refers to this as acid and metalliferous drainage, or AMD. Elsewhere, it is known as metal leaching and acid rock drainage, or ML/ARD, which is the term used in this document. The primary environmental risk associated with ML/ARD is the release of effluent with elevated salinity and/or dissolved metals; this effluent may also be acidic.

Acidic effluent from mine waste, pit walls and mine openings can adversely affect both surface water (i.e., runoff from the WSF) and groundwater. Even if acid-generating weathering of the mine waste does not occur, neutral mine drainage can also contain elevated levels of metals or other constituents of potential concern. Other concerns associated with mine waste effluent include potential contamination of water with chemicals used for processing ore, such as cyanide, petroleum products, oil, solvent, acids, nutrients, floatation agents, etc.

Particulate transport through surface or wind erosion and fugitive dust emissions are also of concern. On-site and off-site effects of such contamination can affect human safety, land use, and/or the downstream/downwind environment. Mine regulations and permit conditions typically require a mine to strictly mitigate or control these impacts.

Waste material must be reclaimed as part of closing or reclaiming a mine site. Whether the waste is reactive or non-reactive will influence specific design criteria, and therefore overall design; but in general, the preferred closure option is site-specific. As such, instead of providing prescriptions, this document focuses on the theory and practice of designing cover systems to aid practitioners, managers, and regulators of the various types of mine wastes working in climatic conditions encountered around the world.

1.2 Scope

The mining companies that comprise the International Network for Acid Prevention (INAP) work collaboratively to address acid drainage. The network presently includes:

- Anglo American;
- Barrick Gold Corporation;
- BHP Billiton;
- Kinross Gold Corporation;
- Newcrest Mining Limited;
- Newmont Mining Corporation;
- Rio Tinto; and
- Teck Resources Limited.

INAP’s objective is to reduce the liability associated with sulphide mine materials by sharing information, transferring technology, and conducting gap-driven research. The network brings together the most recent acid drainage experience and knowledge to build on existing research and avoid duplication of effort, while learning from the achievements and challenges of others, and benefiting from expert peer review on key issues.

INAP contracted O'Kane Consultants Inc. to prepare a technical guidance document that addresses these evolving approaches, one that provides up-to-date information for designers, regulators, and other stakeholders in the design, construction, operation, and monitoring of cover systems for both reactive and non-reactive mine waste during operations and closure. It builds on regional guides and the *GARD Guide*, which was funded and is maintained by INAP.

To date, cover system design guidance that addresses the influence of climate does not exist beyond specific site examples or within a regional context. Case studies that include the full breadth of climatic regions are a key component of this document's attempt to fill that gap.

1.3 Disclaimer

The purpose of this document is to provide guidance on the design, construction, and performance monitoring of cover systems at mine sites globally. The reader assumes full responsibility for any action taken because of the information contained herein.

1.4 Background

Management of mine waste (reactive and non-reactive mine waste) during operations and closure can take advantage of numerous technologies. The *GARD Guide* provides a summary of these technologies. This Global Cover System Guidance Document serves as a continuation from the *GARD Guide* Section 6.6.6, "Engineered Barriers". The design and application of engineered barriers such as cover systems requires an expanded discussion on the information already provided in the *GARD Guide* as their success in managing ML/ARD is strongly dependent on the designers understanding of climate - cover system - waste dynamics.

Cover systems are one of several operational and closure technologies available to manage mine waste. Numerous other region-specific cover system guidance documents are also available. For example, MEND (2012) provides cover system technical guidance for cold regions. In addition, several cover system technical guidance documents offer general guidance from a conceptual perspective on micro-scale and macro-scale mechanisms, and control of these mechanisms. Such documents have been created by:

- Mine Environment Neutral Drainage (MEND, 2012);
- Acid Drainage Technology Initiative (National Mine Reclamation Center, 1998); and
- Environmental Protection Agency (EPA, 1991 and Bonaparte, 2002).

Mine reclamation started in earnest in the 1970s. ML/ARD was recognized as a significant issue and early cover system technologies were designed with the same expectations as liner technologies employed in landfills. The focus of these early liner "type" cover systems was on reducing net percolation (NP) to unrealistically low levels, and stakeholders were often disappointed with the resulting performance. Cover system technology progressed within the landfill industry through work completed by the US Environmental Protection Agency (EPA). As the processes and mechanisms surrounding ML/ARD drew more attention, cover system technology was developed to specifically address current ML/ARD issues in the mining industry.

1.5 General Purpose of Cover Systems

The purpose of a cover system is reclamation of the surface mine waste storage facilities to provide a stable, reliable and sustainable engineered interface between the receiving environment and the mine waste. It supports agreed-upon land uses while minimizing degradation of the surrounding environment following closure (Figure 1-1). For reactive material, minimizing degradation of the surrounding environment typically involves limiting NP and/or controlling oxygen (O_2) ingress during operations following closure.

It is useful to provide an overview of the typical objectives of cover systems, the types of mine waste storage facilities, overarching design factors, and to explore the range of cover systems, from simple to complex. They may be designed to:

- Meet regulatory requirements;
- Divert clean water and reduce the volume of impacted surface water managed on site;
- Isolate chemically reactive waste material;
- Limit upward movement of process-water constituents and oxidation products;
- Limit influx of oxygen and oxidation of certain minerals;
- Limit egress of radiation and radon gas (in the case of uranium mine waste);
- Limit influx of meteoric water to limit oxidation of certain minerals, and limit leaching and dilution of oxidation products;
- Control wind and water erosion of waste material as part of the overall landform stability; and
- Provide a growth medium as the “building blocks” for establishing vegetation and ecosystems.

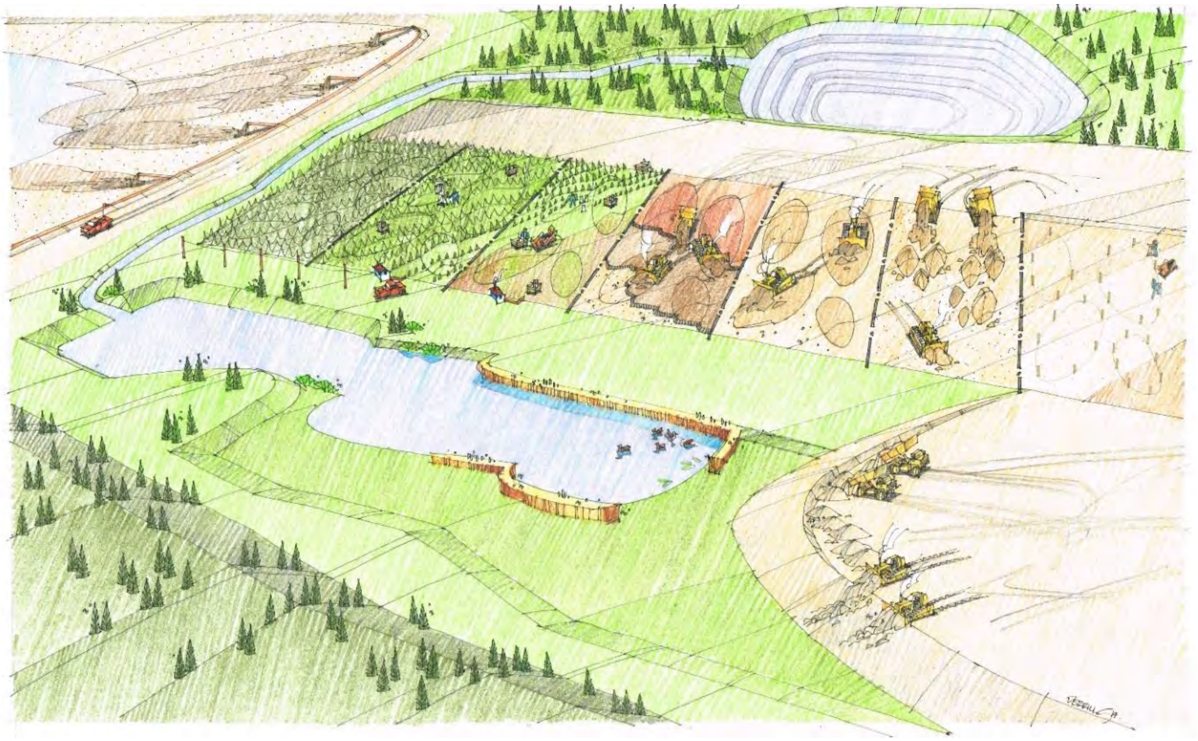

Figure 1-1. Implementation of cover system on surface mine waste storage facilities provide stable, reliable and sustainable engineered interface between the receiving environment and the mine waste. It supports agreed-upon land uses while minimizing degradation of the surrounding environment following closure.

Second to creating a growth medium, most cover systems are aimed at reducing NP to manage chemical loading issues associated with reactive mine material, including chemical loading of the constituents detailed in Chapter 2 of the *GARD Guide*. The constituents of potential concern are often by-products of sulphide mineral oxidation largely related to pH conditions, such as acid rock drainage, neutral mine drainage, saline drainage and metal leaching.

On a site-specific basis, identifying the geochemical issue is fundamental, as it strongly influences cover system design objectives, in addition to outlining performance criteria. In most cases, reducing the quantity of affected water is achieved by reducing net percolation of meteoric water into the mine waste, which in turn reduces effluent seepage volumes. A reduction in seepage volume ideally limits peak concentrations of contaminants in receiving waters to levels that can be assimilated without adverse effects on the aquatic ecosystem. Cover systems can also reduce the hydrograph response to large storm events in the case of sites that utilize effluent water treatment facilities to manage ML/ARD (Section 4.5.3). Much of the capital cost of water treatment plants is associated with infrastructure designed for maximum storm events. By reducing peak flow, the capital costs are lowered even if the cover system is unable to completely eliminate the requirement for water treatment.

In addition to controlling oxygen ingress and net percolation, a well-designed cover system can provide chemical and physical stabilization of stockpiled material and a growth medium for a sustainable vegetation cover.

1.6 Useful Classifications

Common mine waste storage facilities are:

- Waste rock dumps (dumps, rock piles, potentially low-grade ore stockpiles, clay dumps, overburden storage areas, waste rock landforms, rejects, etc.);
- Tailings facilities (tailings ponds, tailings storage facilities, external tailings, etc., these may include the dykes that contain the tailings, soft tailings, and coarse-grained tailings beaches);
- Heap leach facilities; and
- Other mine wastes, such as solid water treatment wastes, flue-gas scrubber wastes, and landfilled wastes.

Most mine wastes continue to undergo physical and chemical change after placement. Cover system designs must account for these changes. At some sites, these wastes may have unusual properties requiring additional care in design. Problem mine wastes may be:

- Liquid or semi-solid (e.g., fluid fine tailings);
- Comprised of highly dispersive clays (e.g., marine shales);
- Highly erodible (e.g., fine-grained tailings sand);
- Water soluble (e.g., salt wastes);
- Subject to large settlements (e.g., low density tailings);
- Radioactive (e.g., uranium mine wastes);
- Subject to self-heating or ignition (e.g., coal wastes);
- Subject to high rates of weathering (e.g., friable mudstone dumps); and
- Likely to contain sewage, solvents, construction debris and other materials.

1.6.1 Overarching Design Factors

Several overarching technical factors arise from general cover system design objectives that dictate site-specific design criteria. Among them are:

- Climate;
- Post-mine land use;
- Waste material physical properties and geometry (e.g., constructability, settlement, slope stability);

- Waste material chemistry (e.g., reactive vs. non-reactive, metal leaching vs. acidic seepage);
- Cover material characteristics and availability;
- Timeframes for establishment of stable and productive landforms; and
- Site access and constructability.

1.6.2 Climates

Adapting the Köppen-Geiger climate system to cover system design and performance, there are four broad ranges of climates addressed in this guide: arid, temperate, tropical, and cold. These climate conditions are described in more detail in Section 6.

1.6.3 Types of Cover Systems

This document classifies cover systems by the following general categories (Section 4.4):

- Erosion-protection systems;
- Store-and-release systems;
- Enhanced store-and-release systems;
- Barrier-type systems;
- Cover systems with engineered layers; and
- Saturated soil or rock cover systems.

1.7 Meeting Performance Expectations

Cover system design, construction, and monitoring as a technology has evolved over the past four decades through research and lessons learned. In the past, some failed to meet selected goals and objectives for the reasons discussed below. While improved understanding of materials, climate and natural processes has reduced instances where cover systems have not met performance expectations (either shortly after construction, or some time later), uncertainty associated with cover system performance continues to pose challenges for mine waste management.

The most appropriate approach to ensure a cover system meets stakeholder expectations, whether these stakeholders be internal or external to the mine operation, is typically a result of one, or more, of the following facets:

- Define and document end land use objectives and expectations for the mine waste landform that considers the landform in the context of the site as a whole;
- Define and document clear objectives for the cover system, which arise from land use objectives and expectations;

- Appropriate characterization of site-specific conditions (climate, materials, hydrogeology, etc.), such that cover system designs from other sites are not simply “transferred” to the current site without a full appreciation of the impact of even small differences between sites on cover system design and performance;
- Consider as a fundamental component of cover systems the concomitant relationship between cover system design, construction, and performance and mine waste landform design, construction, and performance;
- Consider the influence of catchment run-on and lateral groundwater seepage onto and/or into the mine waste landform to ensure understanding for these conditions are included as part of performance expectations for the cover system;
- Ensure surface water management onto, within, and/or from the mine waste landform is considered as part of cover system design;
- Ensure sufficient volume of cover material is available (of the appropriate characteristics, and at the planned unit rate(s)); and
- Appropriate quality control and assurance during cover system construction is achieved.

1.8 Report Structure

This document has two major sections: a high-level presentation of how cover system designs are influenced by their regional context, and case histories that convey the design process and share key lessons learned. The design approach quickly refines cover system options by exploiting, enhancing or combining attributes of a system, specific to a site.

Understanding climate, hydrogeological setting, and how they produce unique micro-climates requires a broad understanding of interacting systems and the dominant operating processes. Major concepts and design fundamentals provide the reader with the knowledge to apply major themes and the general functions of cover systems to specific sites. Designers must look beyond landform-scale water balances to integrate site-wide water management plans with other elements of the landscape.

The section on cover system design also provides a holistic framework for management of reactive and non-reactive materials during operations and at closure. The framework for cover system design is presented at a high level, suitable for readers with minimal technical background. It is presented at a conceptual level, using a hierarchy of climate, geology and materials, and topography, leading to an understanding of the patterns of water movement on a specific landscape. Ultimately, these elements will govern how cover systems perform, and it is up to designers to manipulate them to achieve desired performance. Not all elements of the conceptual framework are currently attainable with today’s science and technology, but this document advocates that this is the direction industry should be headed. Stakeholders and mine planners can use the framework to evaluate cover system design proposals in a hierarchical fashion and ensure important design concepts are considered.

Lessons learned are an important part of the communication. The section on case histories does not highlight specific failures. Instead, it provides an opportunity to disseminate lessons learned on specific sites for the benefit of other sites and propagates a knowledge base that may not have been available during the design or construction process. This knowledge transfer can be thought of in terms of: “If I knew then what I know now, what would I have changed in the original design or construction?”

While the main body of the report is presented at a high level, the appendices focus on the technical details and require a better understanding of mass and water movement in mine waste material and cover materials, particularly flow in unsaturated soils (i.e., unsaturated zone hydrology), the key physics for design of cover systems.

1.9 Terminology

Many specialized terms are used in cover system design, and mine reclamation more generally. Terminology varies by region and some previous works are unclear about certain important issues (such as the difference between infiltration and net percolation), which are central to design and communication. Provided herein is a consistent set of terms, but one that need not replace terminology in a given region.

Actual evapotranspiration (AET)	The sum of evaporation and plant transpiration from the surface to the atmosphere.
Air entry value (AEV)	The negative pore-water pressure (matric suction) required to initiate drainage of a saturated soil.
Available water storage capacity (AWSC)	The difference in volumetric water content between field capacity (FC) and permanent wilting point (PWP).
Field capacity (FC)	The volumetric water content of a soil at which the rate of gravitational drainage becomes negligible relative to the current rate of evaporation or evapotranspiration. Generally measured in the laboratory by measuring the water content of a sample brought into equilibrium in a pressure plate with a suction of 33 kPa (finer-textured soils) or 10 kPa (coarser-textured soils).

Infiltration	Vertical movement of water across the soil surface.
Interflow	Lateral flow that results from a cover system that includes some layering and/or textural contrast (or between the underlying waste and overlying cover material), which results in flow within the overlying cover layer down slope.
K_{sat} and K_{unsat}	Saturated and unsaturated hydraulic conductivity.
Net percolation	Resultant movement of water from the cover layer(s) into underlying waste materials; this water may or may not have originated at the ground surface.
Permafrost	Continuous permafrost is the presence of permanent ground freezing throughout the subsurface. Discontinuous permafrost occurs only in some scattered areas beneath the surface.
Permanent wilting point (PWP)	The volumetric water content at which soil water is no longer available for plant uptake. Although this water content varies by species, it is conventionally defined as the water content at a negative pore-water pressure of 1500 kPa.
Potential evapotranspiration (PET)	The sum of evaporation and plant transpiration that would occur assuming sufficient water is available. It is influenced by radiation, air temperature, humidity and wind speed.
Slope aspect	The main compass direction (north, northeast, east, southeast, south, southwest, west, and northwest) that a slope faces.
Volumetric water content	An expression of water content based on the ratio of the volume of water to the total volume of soil: V_w/V_t. Often expressed as θ.
Water retention curve (WRC)	The relationship between the energy state of the pore-water (matric suction or negative pore-water pressure) and the volume of water stored within the soil pores (volumetric water content).

2 COVER SYSTEMS WITHIN LIFE-OF-MINE

Cover system activities including planning, design, construction, monitoring, and maintenance occur throughout the life-of-mine (LOM). As it pertains to this cover system design guidance document, design should occur at multiple stages in the LOM. Early recognition of the risks in the LOM associated with long-term cover system performance will reduce long-term risk/liability. Therefore, early conceptualization of potential cover system functions and performance may to some extent better inform mining plans and operations if it can be shown to be an economical benefit in reducing future risk and liability.

2.1 Front End Load Engineering

To increase the likelihood of meeting a project's end goals, the variance of cost, schedule, and operating methods must be minimized to optimize the project. This is a challenging task and requires a strategic approach to project evaluation from the very start of a project. Front end load (FEL) engineering is a methodology that takes a deliberate approach to major capital project planning and can have significant impact on the outcome of a project.

FEL engineering is the process for conceptual development of projects, which involves developing sufficient strategic information with which owners can address risk and make decisions to commit resources to maximize the potential for success. FEL engineering includes robust planning and design early in a project's lifecycle (i.e., front end of a project or LOM), at a time when the ability to influence changes in design is relatively high and the cost to make those changes is relatively low. Though it can add a small amount of time and cost to the initial stages of a project, costs can be considered minor compared to the alternative of the costs and effort required to make changes at a later stage in the project.

This Global Cover System Guidance Document provides a framework for FEL engineering to improve conceptualization of cover system design, construction and performance monitoring. The goal being to find a solution that is as simple as possible, but no simpler.

By FEL conceptualization to early planning stages we can provide context for:

1. **Climate**: Developing realistic conceptual understanding of what a cover system can achieve in terms of climate and its seasonality.
2. **Management of oxygen and water:** Developing a realistic conceptual understanding of what a cover system can achieve in terms of site-specific geochemistry and evolution of pore-water seepage.
3. **Landforms:** Developing a realistic conceptual understanding for what a cover system can achieve in terms of landform constraints and the incorporation of a geomorphic approach to landform design.

As this document will demonstrate, the utility of beginning cover system design conceptualization early and often is it prevents inadvertent "painting yourself into a corner" before specific, detailed numerical analysis to support cover system design where design alternatives are severely limited. Figure 2-1 demonstrates a scenario (top) where the conceptualization forms a small percentage of the overall work completed on the project. The information contained in this guidance document provides those tasked with closure and the implementation of cover systems the opportunity to increase early concept work, where opportunities and scenarios are identified, risks are classified, objectives aligned, and simpler solutions identified. It is important that this technique emphasizes risk early on and identifies possible risk reduction strategies. By increasing the scope of investigation early in the LOM (signified by the box breadth), proceeding project activities become more focussed. In this way, any subsequent modelling can begin from a more refined and directed place, and the theory that needs to be put into practice is emphasized.

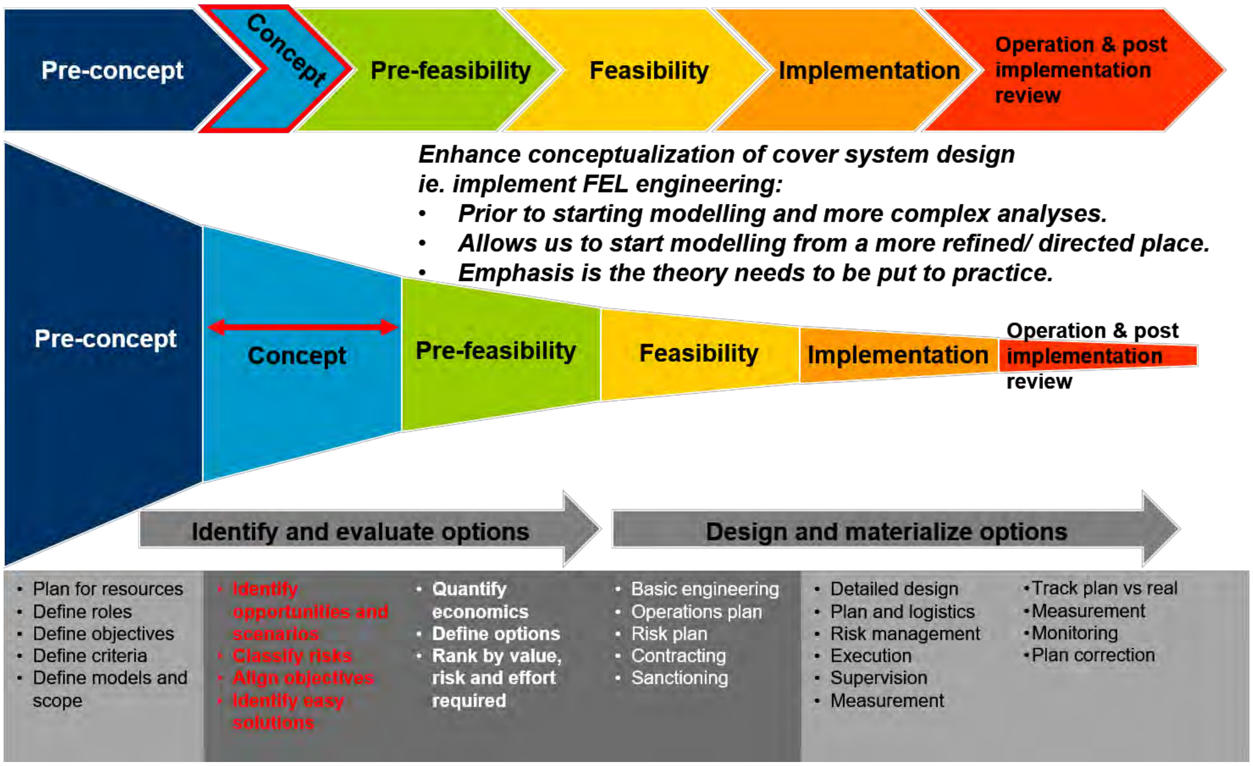

Figure 2-1. Difference between conventional (top) engineering project workflow and front end load engineering workflow (bottom).

2.2 Closure Objectives

Primary closure objectives for most sites are based on final land use plans for each domain of the mine site, as well as on water quality criteria for receiving environments; the objectives vary and are site-specific. Stakeholders and regulators are typically engaged on a site-specific basis in regard to uses for each domain of a mine site, such as open pits, tailings impoundments, leach pads, and waste rock piles. Choosing land use goals is an iterative process (Figure 2-1). Land use plans are site-specific and typically consider the desired land capability of any reclaimed area, and whether isolation or stabilization of reactive material is required to maintain a certain land use capability. The landform, and therefore the cover system, must be designed within the framework set out by the desired land use and the closure objectives.

Design criteria specific to each storage facility or deposit must then be developed to meet the overarching objectives of each facility; examples include limits on contaminant loading in surface water and groundwater receptors, impacts of earthquake events on long-term geotechnical stability, tolerable rates of soil erosion, effects of storm events on surface water management, and desired vegetation. Design of the landform and its cover system work together to meet these criteria. A monitoring program, which begins even before landform construction, measures performance during mining operations and closure against the design criteria.

Performance assessment timeframes provided by the governing regulatory body can be used to determine if a cover system is meeting environment-loading targets. If none are provided, a design life must be specified to assess risk using a probabilistic approach. Failure to specify design timeframes commonly leads to unrealistic expectations for long-term performance. The longevity of a landform (including the cover system) should be evaluated in relation to site-specific physical (including thermal), biological, and chemical processes that will alter as-built performance and subsequently determine long-term performance (INAP, 2003).

2.3 Life-of-Mine

LOM encompasses many of the activities included on Figure 2-2. What is often not recognized is the temporal-scales associated when closure is amended to the LOM.

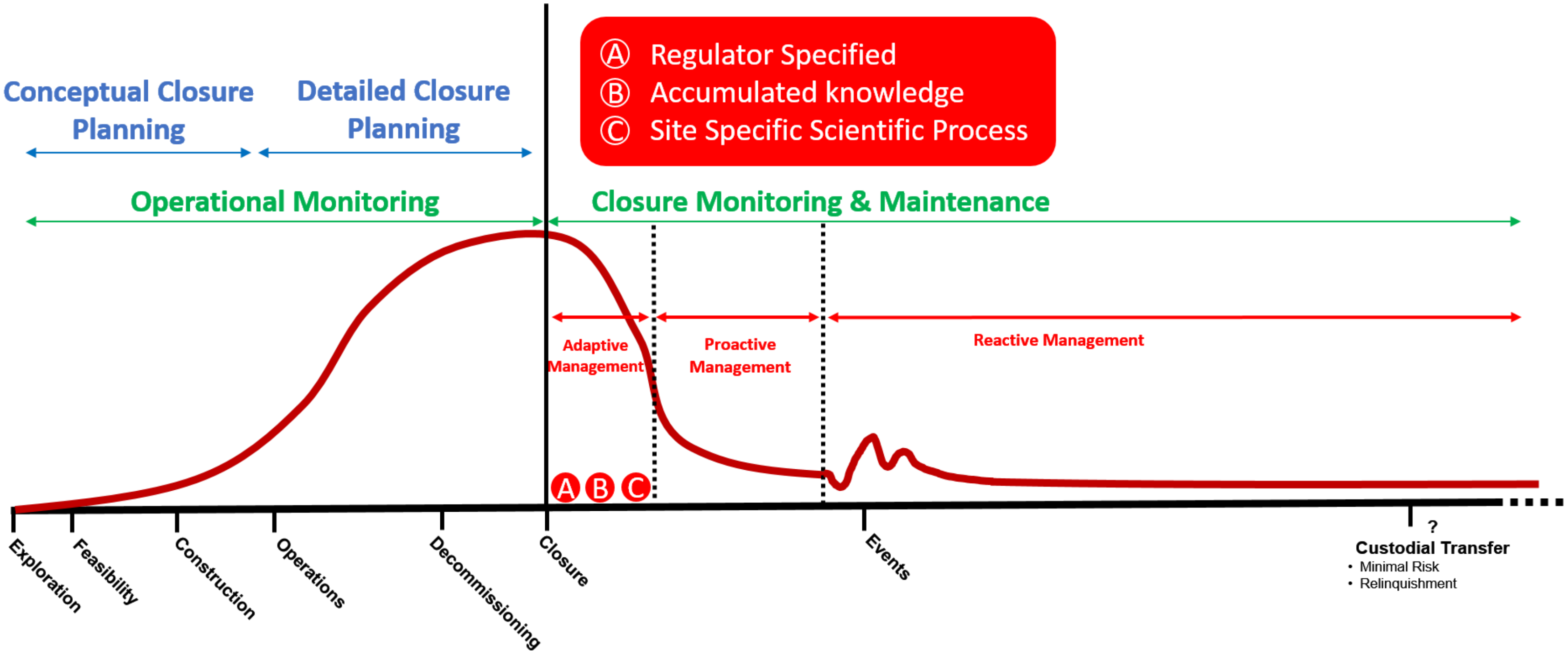

Figure 2-2. Allocation of resources to closure in the context of cover systems.

Cover system design represents different levels of complexity, depending on the stage in the mine life. Cover system design can be divided into three phases:

1. Environmental assessment level cover system design;
2. Operational level cover system design; and
3. Closure level cover system design.

Designs at the environmental assessment level are broadly conceptual and based on previous experience and some initial characterization of the regional climate, or site, if available. Characterization of material available for cover systems may be examined; more commonly wastes are geochemically tested to provide an indication of reactivity. Identifying the risks and potential failure modes of cover systems designs early in the planning process allows knowledge gaps to be identified. Addressing the gaps in knowledge serves to understand, and ideally reduce, uncertainty, all of which informs on risk.

The opportunity to begin enhancing cover system design understanding increases as the operational phase of the mine begins. As waste material is extracted, landforms designed in consort with cover system design can be developed, along with deployment of pilot scale or cover system trials. Operation-level cover system designs allow for evaluation of variations to the conceptual designs against each other within the context of site-specific variables. Understanding risk associated with long-term cover system performance early in LOM will reduce long-term risk/ liability (e.g., salvage and stockpiling run of mine (ROM) non-reactive waste that can be used as cover material). One of the current challenges in the mining industry is carrying forward the closure needs required for cover system design identified early on so that they are valued during the operating stage (e.g., stockpiling important cover materials, or placement timing of ROM materials).

The value of early conceptualization is best illustrated with an example. When approaching the potential use of a cover system on a site, a conceptual understanding of climate, like that advocated by this guidance, forms the basis of what is realistic to expect in terms of performance.

If a hypothetical site experiences annual average potential evaporation (PE) of 2000 mm and an annual average precipitation (PPT) of 800 mm (PE:PPT = 2.5:1), one might assume a store-and-release cover system is suitable based on the relatively large PE compared to PPT input from an average annual perspective. In this case, and this stage of the project, on the basis of the PE:PPT ratio it would not be uncommon for planners to assume that based on a relatively arid climate, expectations for the store-and-release cover system in terms of NP might be in the range of 5% of annual PPT.

As mine sites develop it is not uncommon for there to be various land constraints for WSF footprints on the mine site. Physical obstructions that limit WSF footprints such as water courses, infrastructure, and remediated sites may influence, generally, the manner in which waste rock material is deposited at the angle of repose, which might be 1.5:1. For the originally assumed store-and-release cover system, these slopes may need to be pushed out to 2:1 just simply to place the cover material, and possibly even shallower if erosion of the material is an issue; a reduction in slope may or may not be feasible based on constraints.

However, if climate is further broken down on a conceptual level, more useful information that will refine cover system design is evident. For example, it is not uncommon that the annual trends in PPT and PE display a distinct wet and dry season like many other arid climates. Throughout the year, there are months with PE:PPT ratios are close to 1:1 (during the wet season), and another portion of the year with ratios of 20:1 (during the dry season). This is useful from a cover system designer's perspective in that many risks have been identified depending on the cover system objectives to include:

- Wetting and drying cycles adversely impacting expected performance of compacted clays within the cover system;
- Periods of potential runoff required to prevent high seasonal NP but may come with an increase in the risk of higher erosion rates;
- Drought conditions enhancing oxygen transfer across the cover system;
- Cyclic wetting and drying leading to oxidation of waste in the dry season and flushing in the wet season; and
- Challenges with maintaining vegetation in the dry season (due to lack of plant water availability in the cover profile), which can manage erosion during the wet season and/or is required to meet land use expectations.

Revisiting the original expectation of managing NP to 5% of annual PPT, it may now be evident that radical changes to the design are required to meet this NP performance expectation; for example, the store-and-release cover system may need to be thickened to meet an NP of 5% of annual PPT. Or, it might need to be argued, on a cost benefit basis, that a higher NP rate is acceptable (e.g., 10-15% NP) which will still achieve target seepages based on the conceptual understanding of the geochemistry. However, if 5% NP is a design objective that is "non-negotiable" (i.e., is required for management of solute release to the environment), the FEL conceptualization can provide a basis for re-examining how the design will require revision. For example, incorporation of a lower permeability layer or moving to an enhanced store-and-release cover system may be required at this point. However, employing these types of layers within a cover system would require re-sloping to 3:1 or even 4:1. If footprint obstructions are present, this now necessitates re-handling and hauling material to other portions of the WSF and pushing material upslope at added expense.

Although hypothetical, these are the types of issues commonly encountered when cover system design generally begins to enter the thoughts of closure planners. At this point it is clear that cover system alternatives have been limited and costs are greater for the same closure project. This concept is presented in Figure 2-3; by incorporating more FEL conceptualization for cover system design in the feasibility phase of the project, generally, costs are lower and cover system alternatives more plentiful (Blue Box). However, as time progresses, and the mine operations become the dominant activity, space, resources, and cover systems alternatives become limited (Red Box).

While the above may be obvious to most, the key point is that without appropriate FEL conceptualization of the cover system design, early and often in the LOM, the danger is that an operation will believe they are “operating in the Blue Box” leading up to closure, when in reality they are “operating in the Red Box”. Hence, as designs are refined leading up to closure, the inevitable, which unfortunately is common in the mining industry, is that costs for implementing closure increase.

Simple application of the FEL conceptualization for cover system design as framed within this guidance document will minimize the above from occurring, and therefore optimize the project over the LOM.

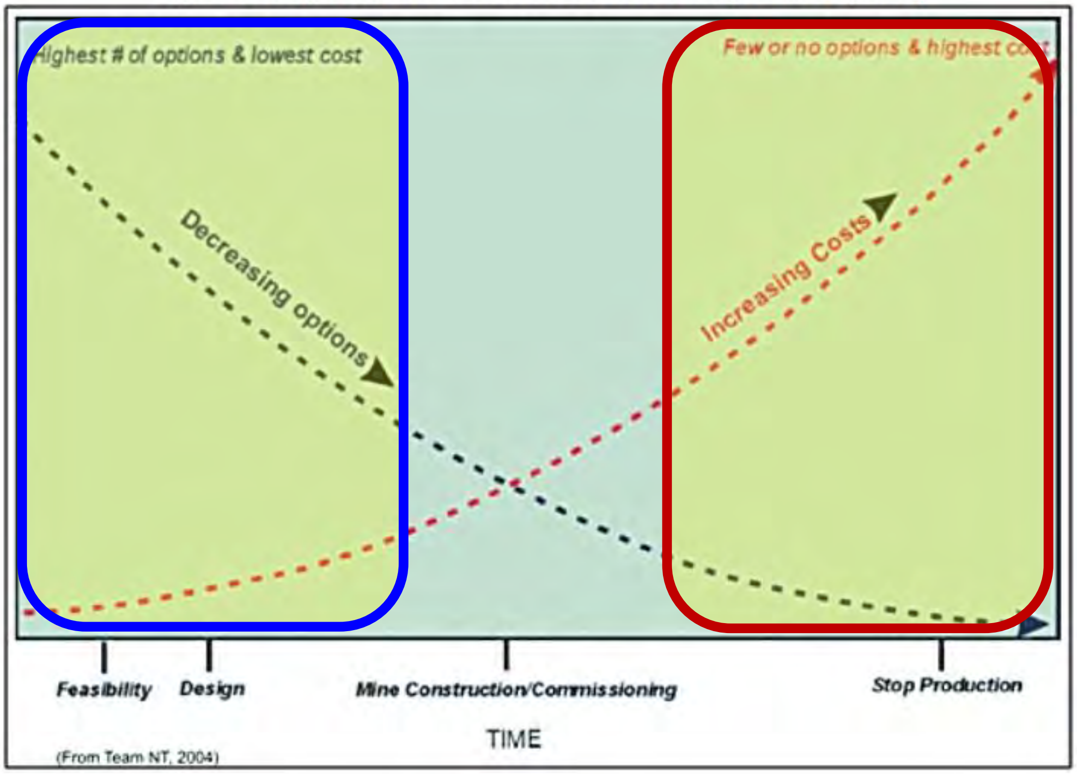

Figure 2-3. The cost versus engineering options relationship as a function of life-of-mine phase.

Risk is the tool for communicating and advocating the importance of cover system design earlier in the LOM and continuing to update the design until detailed cover system design occurs. Presenting the risk and/or liability of delaying conceptualization and what this will mean for closure activities in terms of meeting performance expectations and costs should highlight benefit of early conceptualization, which is why it is emphasized in this document (Figure 2-4).

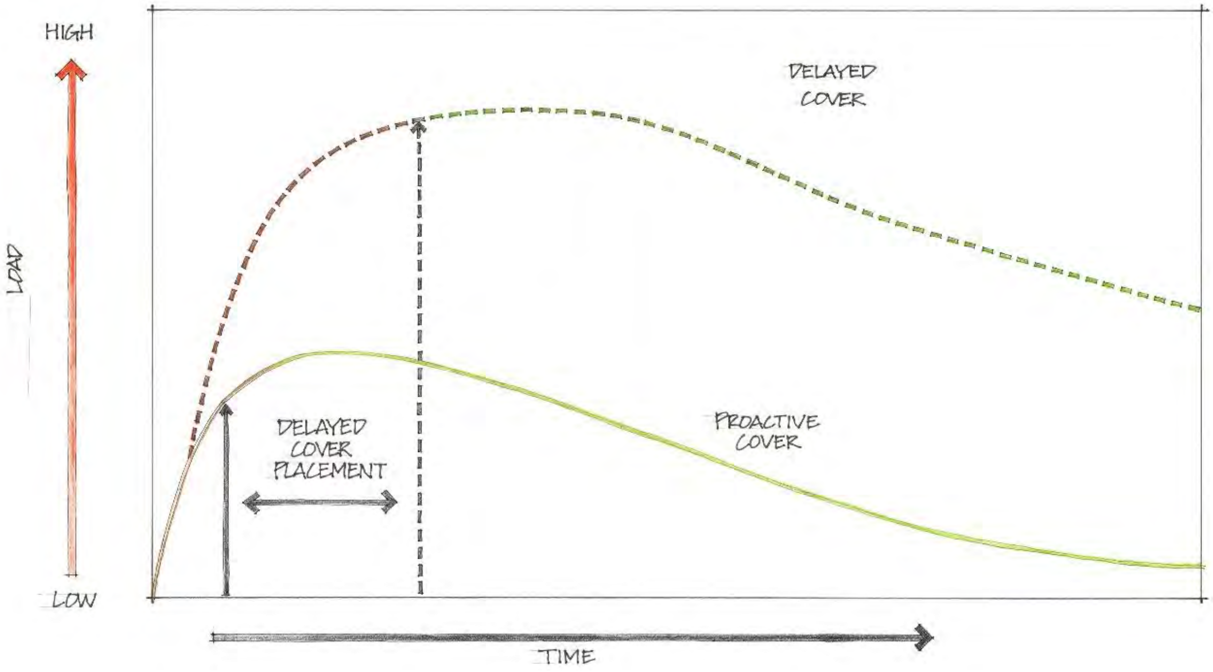

Figure 2-4. Distributed cost of delaying reclamation on the maximum load and total load (integration of curve area).

COST/NPV:

Potential economic benefits of a cover system for prevention/mitigation of ML/ARD versus collection and treatment of mine effluent can be demonstrated using multiple approaches; for example, a net present value (NPV) type of evaluation. Note that this document does not advocate an NPV evaluation, but simply notes that it is a common tool used to evaluate alternatives.

Although NPV is a simple method conceptually, uncertainties surrounding each closure activity, and the assumptions required in applying the technology, make performance-value comparisons challenging and caution is required. All costs associated with the mine closure plan, pre-closure, closure, and post-closure, should be included. Furthermore, while it is obvious that simple components, such as the discount rate, can substantially influence the evaluation used to compare alternatives, this facet is often not appreciated when making comparisons. For example, it is not unreasonable to expect that the discount rate will change from the feasibility stage to the operation stage of a project, and through to implementation of closure. However, the point being is; are potential cover system designs "kept on the table" early in the LOM to address the potential change in discount rate and how this change may influence trade-off study results?

Equally as important is that calculation of costs is highly dependent on technical assumptions underlying each NPV cost comparison. Many assumptions involved in NPV analyses are related to the cover system design; such as effectiveness in reducing NP, the influence on loading reduction, and specifics of the unit costs. In addition, the chosen water management system possesses inherent technical assumptions that are very often inadequately communicated to decision makers, who often are simply presented with the NPV results (and/or the different CAPEX and OPEX for the alternatives). For example, a lack of appreciation for the internal WSF mechanics and geochemistry represents a potential misunderstanding that can propagate into a value used to make decisions. Hence, the breadth of technical assumptions underlying each value must be clearly communicated to decision makers.

2.4 Climate

The Köppen-Geiger climate classification system helps characterize PPT and temperature on a seasonal and annual basis. Both parameters are integral to understanding key physical processes that control water balance and consequently influence NP and oxygen ingress. Although cover systems represent a continuum of function, understanding climate allows a designer to rapidly refine conceptual designs and identify dominant site-specific physical processes that can be exploited and/or enhanced. Climate cannot be modified through engineering, at least to any large extent, and forms the basis of the conceptual design.

A cover system designer should fully understand the dominant climate at a site. All too often a simple average of climate parameters is an input into the models used during the cover system design process. Not only does an average value of precipitation or air temperature result in an unrealistic generalization of conditions, it fails to account for the cycles of variation inherent in all climate signals.

Developing and implementing a greater understanding of the cycles of variability within a climate dataset is essential to cover system design. Long-term temperature signals are, not surprisingly, dominated by an annual signal, but they can also contain indications of a long-term trend of consistently rising (or lowering) temperatures. While the trend may not be dominant, it can explain why the recognition of changing temperatures is difficult to perceive. Typically, the signal of a warming trend is buried within more dominant, smaller-scale, and higher-frequency signals.

Evaluating precipitation typically demonstrates that several scales of variation contribute to the total variance of the system. While no one signal is generally dominant, cover system designers must be aware of all the cycles of variation when designing the system and the implications of potential climate change effects. In using a probabilistic evaluation of meeting cover system performance criteria under climate change scenarios, one can incorporate and evaluate an associated risk.

2.5 Materials

Availability — and scarcity — of cover materials and haul distances from borrow sources is a key factor in developing cover system designs. In general, this facet will substantially influence the optimal cover system design for a site. Transport and placement costs are evaluated against the benefits of utilizing greater volumes and/or more desirable materials. Licensing may also be required to access/use borrow materials, adding substantial, perhaps prohibitive, costs and time to the process. For example, a third party may require that an airstrip at a remote site be left untouched to allow for future land uses (e.g., recreation use; hunting, fishing, etc.), while the material within the airstrip may represent a cost-effective borrow area for cover system construction. There is value in characterizing suitable organic content materials during the pre-disturbance phase of operations, and further value to remove and stockpile these materials. In some jurisdictions, this may be a regulatory condition of the permit.

Scarcity of natural materials often goes hand in hand with increasing variability of material properties. Adequate geochemical and geotechnical characterization of borrow material sources is especially important as material variability increases. Predictions of cover system performance must account for this variability.

Borrow area management must be fully addressed. This should include: access, slope stability, water management (operation and post-closure), management of reject materials, and reclamation. Ideally, borrow can come from within the mining or dump footprints, salvaged and stockpiled ahead of mining. Next best is an on-site borrow and least favourable, an off-site borrow. In cold regions, disturbing land for borrow can lead to permanent permafrost degradation, making good borrow-pit reclamation very challenging. As in dam design, borrow-source identification, characterization, delineation, and access are important — but often neglected — aspects of cover system design.

2.6 Hydrogeological Setting

Climate places fundamental constraints on recharge and discharge relations within a groundwater system. The geological setting includes the boundaries for a given watershed in which the mine waste material is contained. The cover system is part of the landform, which is part of the landscape and its hydrogeology. Cover systems are used to affect the hydrogeology of the mine wastes and their watersheds and understanding the larger site context will give planners the opportunity to assess siting and long-term performance of a waste storage facility.

2.7 Topography

Climate and hydrogeological setting form a basis for narrowing down, or filtering, a list of cover system alternatives. However, the interaction between the two is more important than the individual components. Together they produce unique thermal, hydrological and biological responses and will herein be referred to as "micro-climate."

Micro-climates result in site-specific attributes or characteristics that designers can manage, exploit, or enhance to meet performance criteria objectives. Examples include the influence of solar aspect, temperature/evaporation dependence on elevation, and orographic PPT effects, which can be investigated in greater detail as part of Appendix D. In each micro-climate, subtle changes in setting may produce a unique response. The interaction of micro-climate with the surrounding hydrogeological setting manifests itself as a series of unique water and energy balances at the site scale. While the overarching climate of the site is important, cover systems for reactive mine material must be designed to accommodate the unique characteristics of each micro-climate.

Although climate cannot be manipulated to any significant extent, it is possible to create desirable micro-climatic interactions between landform and landscape. Those resulting responses will primarily affect energy balance and water balance.

2.8 Summary of Cover System Design Framework

Through use of the cover system design framework outlined in this section, an early indication of required functionality for a particular site emerges. Designers can remove potential cover systems from a long list of options at an early conceptual stage and acquire a better understanding of what constitutes realistic performance. A much smaller list of conceptual designs would remain and require more detailed evaluation based on site-specific climate, hydrogeology, materials, and vegetation constraints. The framework also leads to more realistic performance expectations for both NP and oxygen ingress. Therefore, it is advantageous to begin completing a table similar to Table 2-1 as soon as possible, even conceptually.

Table 2-1. Example of conceptual cover design expectations (for net percolation).

NP Range	Design?	NP (%)	Cost $/ha	Water Treatment Reduction	Water Quality Target	Comments
Very Low	Plateau	??%	$??	% ??	?	• Use at other locations? • Meets closure objectives? • Applicability to the site? • Closure planning support studies required?
	Slope	??%	$??	% ??	?	
Low	Plateau	??%	$??	% ??	?	
	Slope	??%	$??	% ??	?	
Moderate	Plateau	??%	$??	% ??	?	
	Slope	??%	$??	% ??	?	
High	Plateau	??%	$??	% ??	?	
	Slope	??%	$??	% ??	?	
Very High	Plateau	??%	$??	% ??	?	
	Slope	??%	$??	% ??	?	

? : represent site-specific values to be determined during early conceptualization.

Table 2-1 acts as a guide and is modified on a site-specific basis. For example, design categories can further divide the landform from the basic plateau and slope portions into each orientation (micro-climate). The table also allows users to evaluate designs based on conceptual performance expectations, limiting the need to evaluate unrealistic scenarios. Although represented above with question marks, in practice the table can be filled in on a site or project specific basis. Many of the values will come from cover system design objectives and criteria, but other will come from operations. Should this not be undertaken, the table forces designers to consider how water will be managed across the landform, and the associated costs of managing water or meeting a water quality target. Determining what the landform and cover system can achieve in terms of reducing water management costs or meeting a water quality target acts as a first attempt at a cost-benefit analysis prior to calculation of NPV.

A similar table can be developed when looking at the ability of a cover system to limit oxygen ingress and/or manage erosion rates.

3 OVERVIEW OF COVER SYSTEM DESIGN APPROACH

3.1 Cover System Design Objectives

The objectives of the cover system are developed in concert with the site-wide closure plan, as depicted by the dashed line connecting these two topics in Figure 3-1. This is the first step of any cover system design process. For example, the design objective may be dust and erosion control to minimize contamination of air, plants, and water from arsenic-containing tailings. In the case of reactive material, the objective may be reducing NP into the waste to reduce contaminant loading to surrounding water bodies to an acceptable level. With clearly defined objectives, the designer has a more defined scope to proceed with site and material characterization and subsequent development of feasible cover system design alternatives. Unfortunately, cover system designs are often developed without considering site-specific impacts. Site-specific objectives allow the needs of all stakeholders to be included in the design process from the beginning. If the initial objectives cannot all be met, they can be revised after field investigations and an impacts analysis (e.g., water quality or ecological risk assessment) are completed and once initial design work is underway.

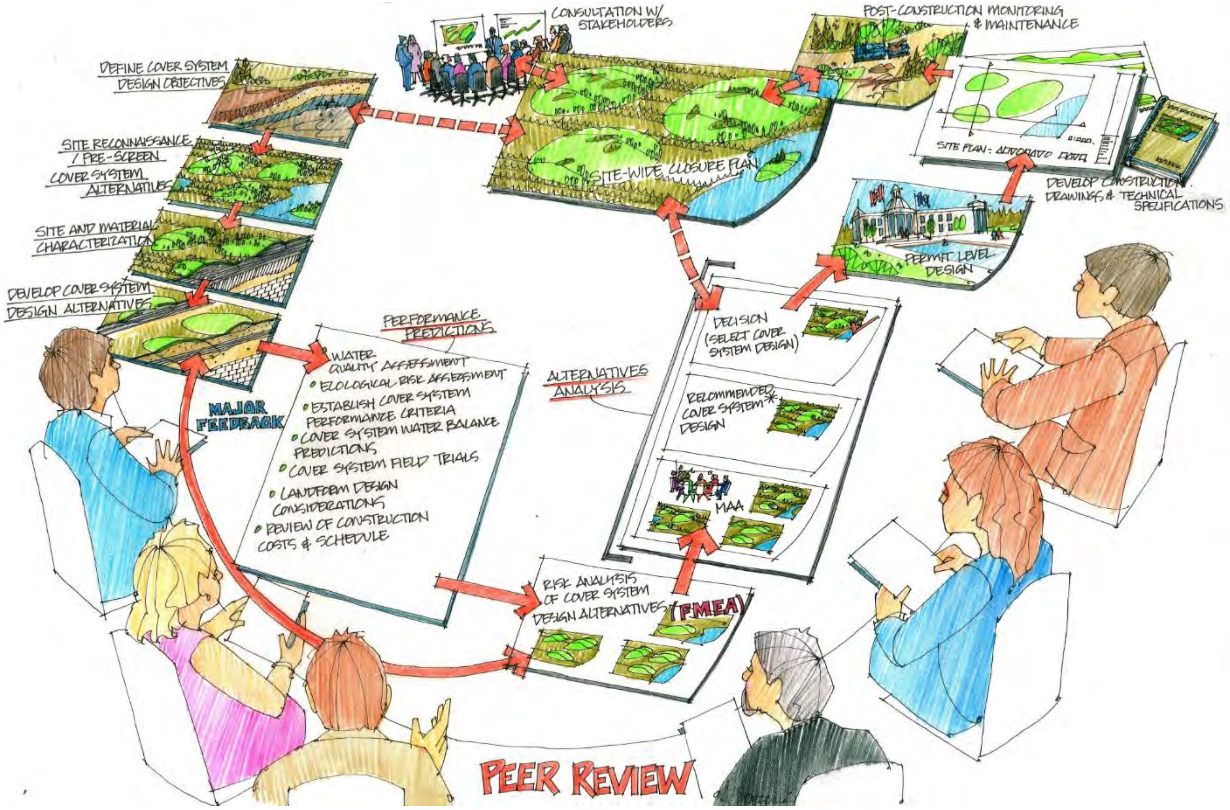

Figure 3-1. Integrated cover system design process (from MEND, 2012).

Cover system design may be primarily analytical (numerical) in nature or more qualitative (or empirical). For example, some elements of the design may require quantitative analyses to ensure that the design is robust regarding fundamental physical or chemical processes (Figure 3-2). In other cases, the design might include objectives that are met by satisfying criteria that are more qualitative in nature and based on conditions consistent with natural systems of a similar end-land use and habitat establishment. In many cases, the more analytical design elements are required to establish foundation conditions, which support the successful implementation of the qualitative design elements. For example, a well-designed water management system (quantitative) may be required to establish conditions on which wetland ecosystem criteria can be applied.

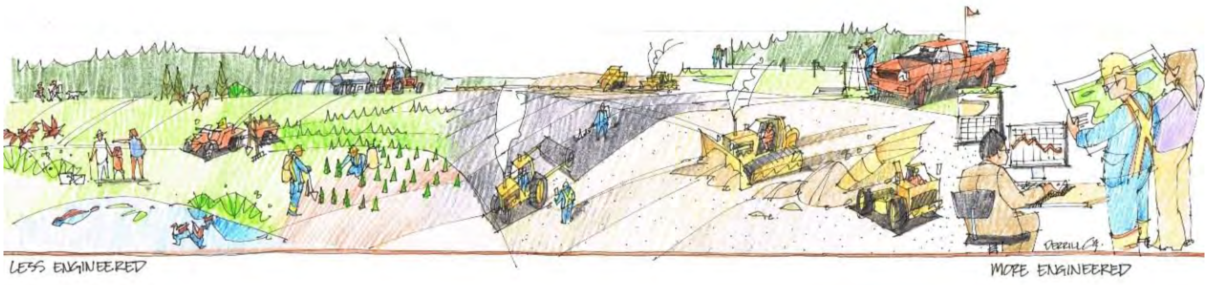

Figure 3-2. Cover system design objective engineering spectrum.

3.1.1 Physical Stability

Dust and erosion of mine waste materials are often controlled through placement of erosion-resistant material or revegetation. Often, use of a nurse crop, gravel, or coarser-textured rock will be required to resist wind and water erosion prior to target vegetation development.[1] Additionally, selective shaping of the landform and/or cover system surface can also be used to manage erosion. For example, hummocks can minimize erosion during rainfall events by retarding the flow of runoff into temporary pools and depressions, although care is needed to manage risk of these surface-shaping treatments compromising other cover objectives, such as net percolation.

Physical and geotechnical stability of the landform and cover system are designed for periods beyond short-term temporary erosion control measures. Closure criteria often stipulates that the landform design must remain stable or meet erosion and/or sediment movement criteria (e.g., tonnes/hectare/year of sediment off the landform). Designs for such long timeframes —

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[1] In temperate climates, establishing vegetation for erosion protection is generally straightforward. It is more challenging in semi-arid areas (characterized by slow growth, minimal cover, high-intensity rainstorms) and in tropical zones (where there are frequent large rainstorms). In many high altitudes and polar areas, vegetation provides little protection against erosion. Use of plants to protect against wind erosion is usually easier than protecting against water erosion. With erosion comes sediment transport and deposition and their respective impacts.

centuries or millennia in the case of radioactive materials — require consideration of how the landform and cover will evolve through time under changing climatic, vegetation, and materials conditions. It also requires periodic monitoring and maintenance.

Stabilizing materials that are highly susceptible to erosion, such as soft tailings, is a unique challenge. To re-grade soft tailings and place cover material requires dewatering the upper tailings profile to provide adequate shear strength and improve trafficability conditions for construction equipment. Draining down tailings by collecting and treating supernatant and seepage waters can often facilitate sufficient trafficability. Placing cover material in multiple thinner lifts may be required to allow consolidation and strength gain at each lift, to avoid slumping or a bearing-capacity failure near the advancing edge of the cover material (Wels et al., 2000). A combination of a geogrid or geotextiles can improve strength, while wick drains can accelerate consolidation of tailings. Another alternative is placement of the cover layers when the upper tailings are frozen, if the climate allows. In this case, it is important to consider the potential for settlement, and differential settlement, following winter placement during thaw of tailings. Surface water management for the cover system will be intimately linked to the settlement-derived characteristics of the tailings (e.g., CEMA, 2014).

Most cover systems are designed to isolate mine waste from the biosphere to reduce direct contact with people, animals, and plants. To that end, the cover may be thicker than the depth of many roots of target plants (agronomic or natural), the burrowing depth of animals in the region, and thick enough to prevent inadvertent penetration by humans, particularly children, where reclamation is occurring in an urban environment. Such designs require specialized knowledge of rooting and burrowing depths, not all of which may be readily available. In many cases, it will not be practical to make the cover thick enough to protect against penetration as many plants have very deep roots and some animals burrow far down. Depths vary with geography and material type (i.e., on a site-specific basis), and in some cases, practical thicknesses must suffice. In other situations, plant and animal control over long periods may be required.

3.1.2 Chemical Stability

The level of reactivity and buffering capacity of reactive materials are critical in determining design objectives. In general, reactive waste dictates that the cover system meets a “higher performance expectation” to reduce contaminant releases to acceptable levels (MEND, 2004). In most cases, a higher performance expectation implies a lower NP rate to underlying reactive material to limit leaching and solubility, and/or control of oxygen ingress to limit weathering of reactive material. Further discussion on chemical stabilization is provided in Section 4, including kinetic and solubility control mechanisms.

3.1.3 Meeting Land Use Expectations

Mining is typically viewed as a temporary use of land and designing towards future land uses that are desirable to local communities and regulators is typically required. The potential use of these areas may appear to be limited due to the potential for damage to the cover system and the human health and environmental risks related to elevated metal concentrations or other constituents of potential concern in the underlying material. Long-term settlement can also limit construction of buildings and roads. In practice, however, there is a substantial list of potential uses, and planning for them before mining begins provides for the most flexibility.

End land uses for mine sites are extremely varied. In general, mines in remote areas are often reclaimed for wildlife habitat/natural area. Mines in urban areas are often redeveloped to meet industrial, commercial, recreational, and residential expectations. In other cases, a reclaimed mine may be fenced off (often due to contamination or slope stability issues), allowing only highly restricted access. This amounts to the mining becoming a permanent use of the land and effectively sterilizing it for other uses.

Meeting land use expectations often includes a prescribed habitat type, vegetation structure and ecosystem capability. Often there are requirements to meet off-site natural reference conditions (Hayden-Wing, 2013). There may be a requirement for “percent cover” of certain species of vegetation (Berger, 2002), soil capability (CEMA, 2009), certain crop productivity and yields for agricultural land (USDA, 2006), and creation of certain habitat for wildlife (e.g., Eaton et al., 2013).

The landform and cover system, its resulting performance in terms of managing erosion, and release of any contaminants of concern may also be specifically linked to valued components of the post-closure ecosystem or landscape. By designing a landform and cover system that fosters a desired and predictable ecosystem trajectory, the likelihood of minimizing adverse impacts to valued ecosystem components can be demonstrated.

Different jurisdictions have different approaches to revegetation. Some favour agronomic species, especially for erosion control and for end land uses involving farming, while others favour native species. There is a general trend toward use of native species to meet ecological needs (McKenna, 2002). Rapidly establishing nurse agronomic species may be required if native vegetation growth is too slow, thus failing to provide stabilization to the overall design. In many cases the use of agronomic grasses can lead to a pseudo-climax vegetative cover (SRK Consulting, 2014) that may preclude establishment of native ecosystems for centuries to come. In short, revegetation (reclamation) objectives are site-specific. However, regardless of the objective (if vegetation is determined to be required for the land use), the cover system must provide an adequate rooting zone for target species while minimizing the potential for uptake of metals or other constituents from the cover or the mine waste below.

An important consideration in meeting final end land use expectations is to understand what those expectations are early in the planning process. This is done through early and regular engagement with local/community stakeholders. This ensures any expectations are integrated into the conceptual and final detailed designs, and not simply added to the final design in an unsupported manner.

3.1.4 Summary of Objectives

A successful cover system hinges on crafting realistic end land use goals, objectives for the landform, design and performance criteria for the cover system over specific timeframes. Developing at least the first, if not first two of these objectives, is typically undertaken as part of closure planning and ideally in collaboration with stakeholders. Physical stabilization of the landform and cover system is central to all cover systems, and chemical stabilization is also a common objective. In addition, care must be taken to define, on a site-specific basis and possibly a landform-specific basis, what is meant by subjective terms that are often utilized as part of establishing cover system and landform objectives. For example, the terms "stable" and "stabilization", are subjective terms that can be challenging to demonstrate having been achieved without some form of site-specific definition. Finally, meeting appropriate site-specific land uses is typically important to most mines. Cover systems are generally central to all these three complementary, albeit sometimes competing, sets of objectives. Declaration of these objectives is central to achieving successful cover systems.

3.2 Cover System Design Approach

This methodology ensures that a closure plan is not only technically the best option, but cost-effective with the appropriate balance of capital and operating expenditure, but is also implementable, and meets stakeholder expectations. This also makes use of a progressive plan of stakeholder engagement, internal options assessments, and fit-for-purpose engineering designs to develop cost estimates to the appropriate target level of accuracy for the stage of the project. The methodology is described in detail below.

3.2.1 Knowledge Base

3.2.1.1 Background Review

The objective of this task is to consolidate understanding of site conditions using existing site information and studies, including:

- Climate;
- Hydrogeology;
- Hydrology;
- Physical condition, field measurements;
- Observations, etc.; and
- Legal obligations.

A key component of the background review is site visits and interviews with staff. For the staff interviews, targeting key personnel, and documenting the entire interview process using questionnaires, recordings, and transcripts will prove beneficial.

Site visits will be an important step to further understanding of local conditions and to ensure the design/closure team has a grasp of the logistical requirements of completing works on site. This knowledge will be invaluable for identifying potential hazards ahead of further on ground activities, to ensure additional studies are undertaken in a safe and efficient manner.

Site reconnaissance is a fundamental step for cover system design projects to develop the site and material investigation program. Based on a preliminary assessment of the reactivity of the waste materials and available borrow materials for cover construction, possible cover system designs can be pre-screened to develop design alternatives for further analysis. Tasks that are typically completed during preliminary site assessment include:

- Air photo interpretation and terrain analysis to map potential borrow sources, terrain features, natural landforms as analogues for landform design, and native vegetation;
- Search of site and company archives for historical investigations on geochemistry, available borrow materials, and their characteristics (hydrogeology, hydrology, etc.); and
- Collection of digital photos and digital terrain models of pertinent objects, including the waste storage facility, potential borrow areas, seepage faces, and native vegetation.

3.2.1.2 Develop Conceptual Model

Preliminary conceptual models of the sites will be developed based on the background review to identify key processes and mechanisms, and their respective controls, that are expected to influence performance.

The conceptual model then becomes a key stakeholder communication tool and can be used to facilitate discussions across technical disciplines and key stakeholders alike, to identify and highlight risks and explore potential solutions. The process of developing the conceptual models will also allow for clearly identifying and articulating data gaps. The conceptual models will be refined, where appropriate, following the gap and data analysis.

3.2.1.3 Baseline Qualitative Risk Assessment and Failure Modes and Effects Analysis

Baseline Qualitative Risk Assessment collaborative workshops should follow the development of each conceptual model. A well-established risk assessment approach may already exist within an organization and should be used for this workshop. This process will identify material and non-material risks, existing controls, and knowledge gaps. It will determine the tolerance of the risks in the context of the project. Identification of risks will use standard criteria, such as health and safety, environment, community, reputation, legal, and financial. Workshops require participation of key personnel knowledgeable regarding historic operations of each site, to capture information that has not previously been recorded in the available literature and to provide pragmatic advice to the technical closure specialists with regards to location specific limitations.

The basic message is that: while it is a given that risk-based decisions are most often used to determine a path forward, very often these decisions are done “within closed doors”, and/or poorly documented/communicated, and/or undertaken without the site’s risk profile.

All these issues are why this document advocates use of the failure modes and effects analysis (FMEA) approach as an engineering design tool throughout all stages of cover system design to address the fact that cover systems and landforms involve complex and interactive facets. The FMEA process provides a more detailed examination of the potential cover system design, construction and/or performance issues and the subsequent health and safety, environment, community, reputation, legal, and/or financial implications. Where cover system and landform issues are particularly complex, the FMEA approach expedites identification and evaluation of the alternatives. Although there are two ways to communicate risk, cover systems in the context of closure timeframes are better suited to employ a probability-based method using numerical outputs. Alternatively, for shorter timeframes, a qualitative risk assessment can be used. Each method should be selected with care, ensuring it communicates design risk effectively, and reflects the site’s current risk profile.

3.2.2 Address Knowledge Gaps

The Baseline Qualitative Risk Assessment (and potentially the FMEA) workshop will identify remaining areas of uncertainty (gaps), which in turn inform on risk. These areas of risk will directly inform on the scope required for the additional studies. Therefore, using the output from both the

Baseline Qualitative Risk Assessment and the FMEA, as a project evolves and the cover system design becomes more detailed, the minimum technical works required to address risks that are intolerable, or not well controlled, will be identified. The approach can thus provide the necessary information to address these risks in a cost-effective manner. In short, as the project evolves, it is the potential failure modes and application of a risked-based framework that remains consistent, as more information is developed, and the conceptual model is enhanced.

Appropriate site characterization is critical for the design of a sustainable mine waste cover system. The following elements should be characterized when a cover system is being considered:

- Development of long-term climatic data set for design and consideration of possible/probable changes in long-term climate change;
- Geochemical and geotechnical characteristics of the waste material;
- Hydrogeological setting of the waste storage facility;
- Availability of potential cover materials and their characteristics (volume, suitability, variability, access, and ownership);
- Impact of removal of cover material from borrow areas;
- Availability and characteristics of materials suitable as growth media, where revegetation is desired; and
- Surrounding vegetation (to guide revegetation planning, provide information on probable mature plant communities, assist in development of long-term water balances for the cover system, and provide information on probable ingress of volunteer vegetation where revegetation is not desired).

As the technical studies are completed, the conceptual model for the cover system and landform will be updated (if required), and where appropriate, the risk assessment and risk ratings reviewed to reflect the updated knowledge.

3.2.3 Identification and Evaluation of Cover System and Landform Alternatives

Selection of cover system design alternatives for a waste storage facility are based on climatic conditions, available cover materials, and the specified design objectives of the cover system. Design alternatives must be tailored to the characteristics of the site and not chosen solely because the design “worked at another site”. Consideration of the chemical, physical, and biological processes that could alter the properties of the cover material (e.g., saturated hydraulic conductivity), and thus influence long-term performance of the cover system, is included in this design stage (INAP, 2003).

This approach, which should encompass different aspects, slopes, and therefore varying thermal regimes, greatly reduces the potential for fatal flaws in the design, which may not be identified by simply applying a design that "worked at another site". Spatial variability is an important factor with respect to frost heave, settlement, ponding, etc. To manage variations in the landform, more than one cover system design might be needed for closure of a single waste storage facility. Finally, consideration is given to constructability, complexity, and challenges with quality assurance and control, in the conceptual cover system design stage.

3.2.3.1 Assess Alternatives

Typically, cover systems and the associated landforms are but a single component of a site-wide closure plan, although these two aspects can be the key aspects of closure. This makes evaluation of alternative cover systems and landform designs a necessary part of site-wide closure planning.

Hockley (2014) advocates the use of a non-duality approach in which the level of complexity in the tool, or framework, used for the alternatives evaluation is commensurate with the complexity of the system being evaluated. For example, given a single mine waste landform with no water treatment and minimal stakeholder involvement, an alternatives evaluation might only need to be qualitative, with the preferred alternative determined through documented discussion. For a situation with multiple landforms (e.g., open pits, TSFs, WRDs), the potential for water treatment, and a high level of stakeholder involvement, the evaluation should be much more quantitative. For example, a multiple accounts analysis approach is a multi-stakeholder, multi-disciplinary tool that can help evaluators weigh the relative benefits and costs (or losses) of alternatives from an array of options.

Regardless of which decision-analysis tool is used, they should only be used to help document and evaluate the various opinions and options; in other words, inform on "the decision", and not be relied upon solely to make "the decision".

3.2.3.2 FMEA and Risk Analyses on Preferred Alternative(s)

Evaluation of the benefits of conducting a second FMEA should be considered once new information and results of studies identified as part of the first FMEA are available. With the additional information, the second (or subsequent) FMEA provides a straightforward opportunity to communicate and understand risk across a wide range of stakeholders. In this way, how uncertainty and risk were identified, and how the latter was mitigated through the design process can be demonstrated to stakeholders. Each stakeholder will assess the design through their own driver, or lens, to evaluate and understand how risk was mitigated. During this exercise, the language of the presentation is important: that designers are not just telling stakeholders what "the right answer is", but that the design still has risk which has been reduced through addressing uncertainty or other aspects of the design. Ultimately, the potential risks have been mitigated to an acceptable level.

While numerous methods are commonly used to compare the advantages and disadvantages of various alternatives for reclaiming a mine waste storage facility, this guidance document advocates use of the FMEA approach as an effective means of communicating and quantifying risk to stakeholders; Robertson and Shaw (2006) describe the FMEA approach in detail. FMEA is a methodology for assessing risk, combining the likelihood and consequences of failure. Its value and effectiveness are tied to the ability of knowledgeable and experienced experts to participate. The evaluation will identify failure modes, estimated risks, and appropriate mitigation measures proposed. Once failure modes and measures with the greatest risk are identified, possible mitigation or alternative designs to reduce risks may be developed. FMEAs are an essential part of the design process in which risk- and liability-reduction are required.

Implementing the FMEA tool on a base case and alternatives allows all perspectives to be evaluated on the same footing. Most importantly though, is that it identifies and acknowledges risk within an alternative. In other words, it changes the language for communicating the alternative in its ability to meet objectives from one of – "this alternative is the correct one and the other ones are incorrect" – to a message of – "risks have been systematically identified for the alternative and consensus has been achieved that these risks can be managed in a transparent and cost-effective manner". Ideally the project design team possesses substantial experience with weaving this risk framework within alternatives assessment and refinement such that a defensible methodology is utilized to ensure a cover system and landform design that is not only technically the best option, but also cost-effective with the appropriate balance of capital and operating expenditure, executable, and meets stakeholder expectations.

The FMEA process also allows the designer to modify aspects of the cover system design that present unacceptable levels of risk. Equally as important, the FMEA process allows one to document and communicate these modifications and the rationale for the changes. The modified cover system design, supported by the FMEA results, then becomes a powerful tool for conveying closure strategies and closure objectives.

This approach allows for options to remain "on the table" longer as concepts, gaining more knowledge based on the high-risk attributes of the design. Only once the FMEAs identify knowledge gaps for a design, and those gaps addressed through further investigation, can design alternatives be removed from consideration. In this way, design alternatives that conceptually may have never been considered due to lack of knowledge and/or high associated risk may now be considered. Conversely, if the standard approach is used on a single design, this may result in projects delays or excess cost in having to circle back to design alternatives previously discarded.

In conclusion, FMEAs should be conducted early and often throughout the cover system design process to help focus resources to help mitigate risks. Results from an FMEA can also be used as a formal communication tool to convey risks to the various stakeholders and so those not intimately involved in the early design phases understand the basis for design alternatives.

3.2.4 Engineering and Costing of a Preferred Alternative

With agreement on a preferred alternative, costing of the preferred alternatives for each landform and/or component of the landform and preparation/update of implementation plans can proceed.

The selected alternative during previous stages can be further developed to a level suitable for a more stringent cost estimate (if required). As a minimum general arrangement, domain specific layout, surface water catchment, typical earthwork sections and details, waste cover system and typical landform details, typical surface reshaping and rehabilitation, and revegetation conceptual design drawings must be developed. The break down structure of the work developed in the drawings must be utilized to develop site and domain specific "bills" of quantities also sufficient for detailed cost estimates.

At this stage, a common misunderstanding in engineering a preferred cover system design is the fundamental importance of developing appropriate material movement quantities and methodologies associated with creating the landform associated with the cover system. For example, in early stages of cover system design alternatives evaluation, designers often assume that to create the appropriate landform all materials can be simply "pushed down", and that only a "high level" cut-fill balance is required for creating the landform.

This guidance document advocates that much greater attention be given to "getting the volumes for material movement right" at the earliest opportunity in the cover system design process. A lack of attention to this aspect early in the cover system and landform design process, which is typically left to the more detailed engineering design stage of a project, will very often lead to cost implications to the project (i.e., higher costs). For example, as with the FEL conceptualization discussed earlier within this document, pushing material down a slope of a landform to create a desired slope profile results in a much different unit volume cost, as compared to pushing the material up a slope and/or picking up the material from within the slope (where these latter two slope alternation methods may be required to address crest and toe constraints).

A second facet in cover system and landform design that can also substantially influence material volumes and unit rates, and therefore costs, is establishment of an "end-of-pipe" invert elevation for surface water management associated with the mine waste landform and cover system design. In other words:

- If surface water management off a covered mine waste landform is deemed as being a fundamental aspect of the design and expected, which is typically the case; and
- The final elevation for surface water management off, or within, the landform is not established early in the design process; then
- Substantial re-working of the landform design may be required, at additional cost, once detailed designs are considered.

3.3 Climate Controls

A continuum of performance for NP rates for a cover system exists for different climate regimes. Within a single climatic regime, the same continuum may be a result of the influence of differing abilities of a cover system to enhance evapotranspiration (ET) and to promote runoff from the landform. First, dominant mechanisms required for a cover system must be identified, given climatological and hydrogeological constraints.

The continuum of cover system performance is presented conceptually in terms of "very low," "low," "moderate", "high", and "very high" NP, oxygen ingress and erosion rates. The qualitative descriptors are common across sites and climates, although their nominal performance values will differ. For example, the very low NP rate for a cover system in a tropical climate will still be greater than those for a cover system providing very low rates in an arid environment (Figure 3-3).

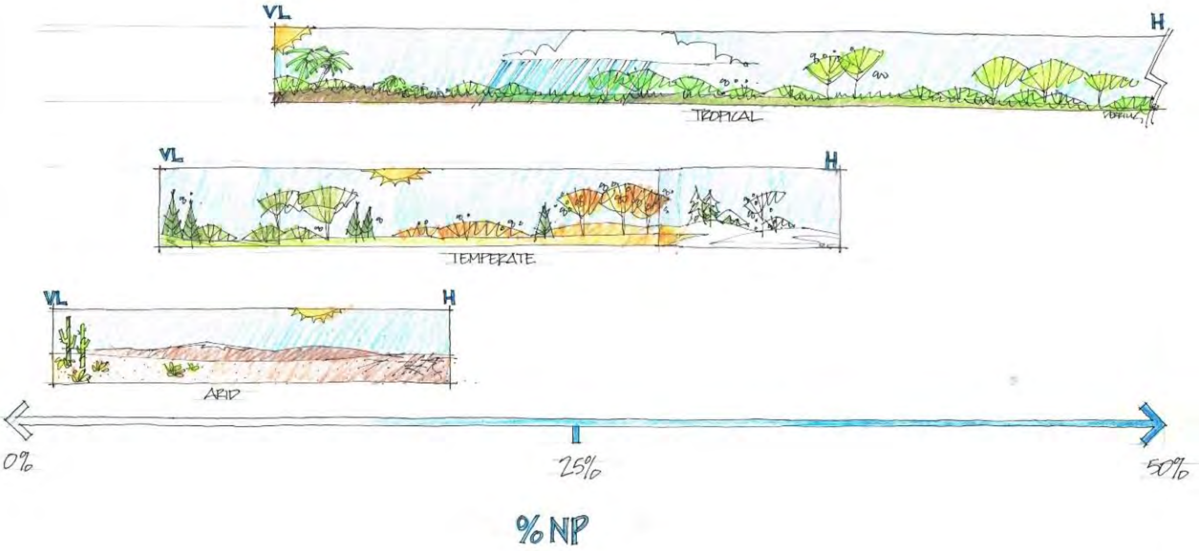

Figure 3-3. Qualitative NP rates for arid tropical and temperate regimes.

The numerical values associated with the performance continuum will depend on site-specific climate, geology, materials, and topography. Unrealistic expectations can result in challenges with meeting cover system performance expectations (Section 1.7). For example, in tropical climates characterized by a large water surplus, a realistically very low NP rate would be approximately 10% of annual precipitation. Conversely, very low NP rates for an arid site may be in the range of 1% of total annual precipitation due to low annual precipitation compared with the relatively stronger evaporative capacity. Qualitative cover system performance will vary in each climate due largely to seasonality (Section 5) and the types of material encountered (Appendix B). Temperate climates that involve dry winters and hot summers (a Cwa climate as per Köppen-Geiger) will occur at one end of the performance continuum near "very low," while a Cfc (temperate, no dry season, cold summer) climate may represent the "high" end member.

3.4 Climate Control on Oxygen

The availability of oxygen is an important control on internal geochemical mechanisms of reactive mine waste. Before using cover systems as a tool to limit oxidation and the concomitant chemical loading associated with the ingress of oxygen, an assessment must be conducted as to whether oxygen can be restricted sufficiently using a cover system within a given climate, material set and hydrogeological setting. Furthermore, consideration is required for whether the availability of oxygen to pore-air space during waste placement may have resulted in sufficient development of stored oxidation products such that management of oxygen by the cover system becomes much less important, as compared to management of NP and leaching of stored products.

The continuum for controlling oxygen is not as widespread as with NP. Based on the exponential relationship between oxygen diffusion and the degree of saturation of porous media, as well as that for air permeability, controlling oxygen in terms of cover system performance can generally be thought of as either "very low" or "high to very high." In this document, the ingress of oxygen is compared, or bench-marked by, a strict level control. It is defined by diffusion of oxygen across an ~1 m depth of water overlying nominally reactive tailings; for this general arrangement, oxygen ingress is in the range of 1 mole O_2/m^2/year.

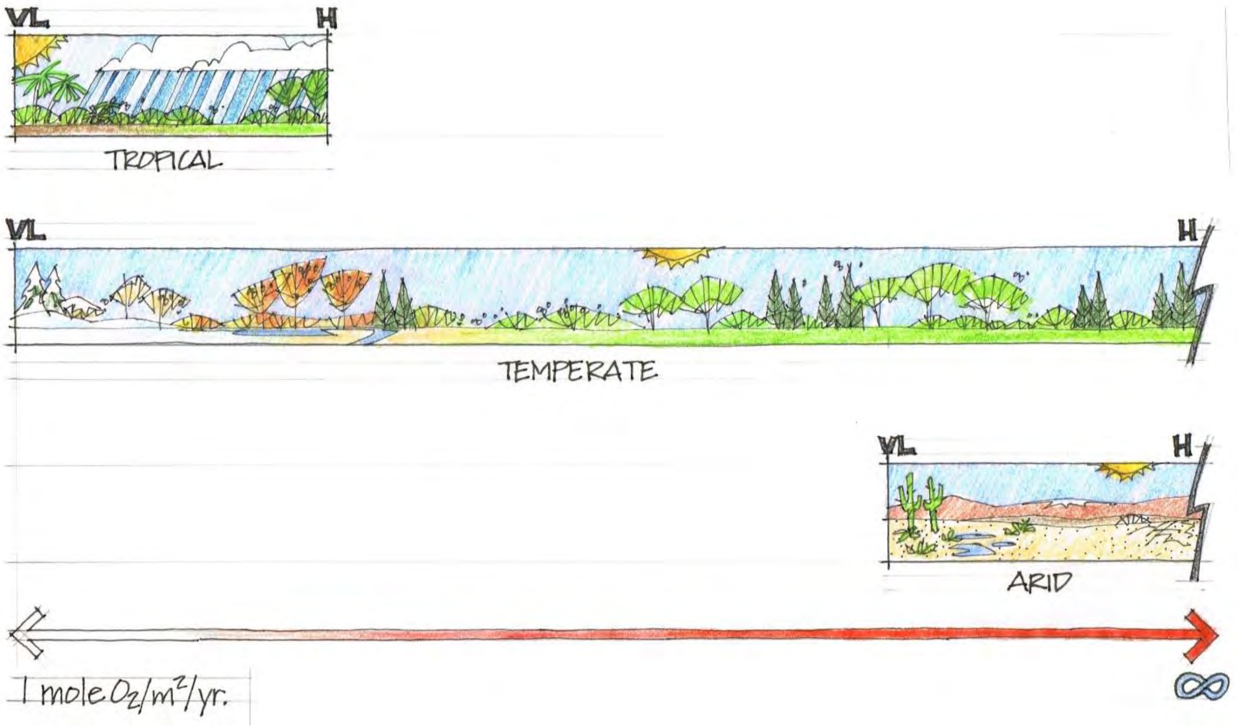

Figure 3-4. Qualitative oxygen ingress rates for arid tropical and temperate regimes.

Conceptually, the alternate end member could be considered infinite. For example, depending on geochemical characteristics of the reactive waste material, and internal waste storage facility hydraulic conditions, the difference between 100 and 10,000 moles O_2/m^2/year may make little difference in the potential geochemical load generated within the waste. And of course, this also depends on whether the waste material is coarser-textured (e.g., waste rock), or finer-textured (e.g., tailings).

To classify the performance continuum for each climate type, management of water resources for internal cover system processes is critical. Where large surpluses of water exist, backfilled pits or submerged mine wastes are often employed to prevent oxygen ingress. When the climate can sustain high degrees of saturation (>85%) within a cover system annually, results for these "tension-saturated" cover systems can be like a water cover. Arid climates do not possess enough excess water to sustain high saturations annually in a cover system. For tropical climates, it is difficult to create anything but a cover system that maintains high saturation conditions, thus limiting oxygen ingress to the underlying mine waste material (Figure 3-4).

3.5 Climate Control on Erosion Potential

Qualitative erosion rates follow a more complex continuum of performance (Figure 3-5). The mechanisms in Section 4.2.3, as well as the relationship demonstrated in Figure 4-3, highlight the importance of slope (topography), materials, vegetation, and climate. Erosion of cover systems is typically most concentrated immediately following construction, before vegetation establishes. Climates that are more conducive to rapidly establishing vegetation (increased solar radiation and soil moisture) will generally allow for better erosion management. Tropical climate growing seasons persist throughout the year, are not moisture-limited and receive adequate solar radiation for enhanced photosynthesis. As a result, the timing of revegetation is not as critical as it is in climates with distinct wet and dry seasons, or those with non-growing seasons.

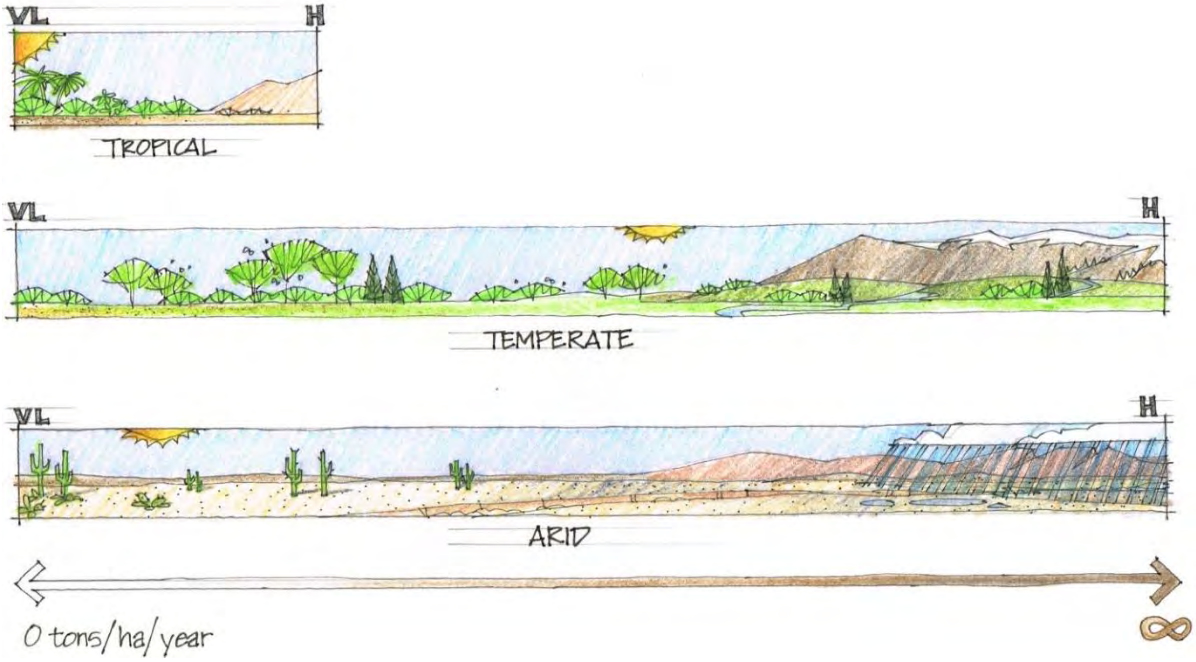

Figure 3-5. Qualitative erosion rates for arid tropical and temperate regimes.

Temperate climates that nearly border arid climates adjacent to tropical regions exhibit significant differences. Erosion potential can be mitigated by rapid vegetation establishment in more Cfb climates with warm summers and no pronounced dry season. "High" erosion rates in temperate climates are more likely to occur in Cwa climates due to the challenges with establishing vegetation quickly in hot growing seasons, with high water demand following a dry winter. Arid climates can span a full range of cover system erosion performance (Figure 3-5). For extremely dry climates that receive little rainfall, the potential of erosion is very little to almost none (not considering the potential for wind erosion, which is highly site-specific). Alternatively, some arid climates receive very little precipitation on an annual basis, but the rain that is received occurs in high intensity, low-frequency events (monsoons or intense thunderstorms). Any water falling on the cover quickly evaporates after the storm ends and erosion occurs.

3.6 Climate Variability/Climate Change

Successful closure designs rely heavily on the interaction of climate, geology, hydrology, hydrogeology, vegetation development, and topography. The amount and timing of water availability are controlled by the regional climate. However, the primary parameters of PPT and temperature are not static but vary on a seasonal, annual, and decadal basis. Climate is non-stationary, and consequently must be considered when evaluating water availability.

3.6.1 Climate Cycles

Average annual PPT and PE data are of limited value in landscape design and performance modelling. Rather, probabilities of achieving design criteria and performance markers on seasonal and decadal timescales are considered. Within each historical climate record, repeating cycles of drying and wetting are evident with unique frequencies. Climate cycles themselves vary in frequency, with minor temporal variations from one cycle to the next. Identifying cycles in the historical record and forecasting likely conditions relevant to the construction timeline provides a powerful tool to cover system designers (Figure 3-6). Large-scale climate anomalies could lead to either anomalously dry or wet climates.

The variability in hydrologic response to global climate cycles (e.g., Pacific Decadal Oscillation, El Niño/Southern Oscillation, etc.) is incorporated in landscape design to accommodate periods of amplified water surplus or deficit, although there is a need to better quantify these cycles and evaluate their interacting effects (Mwale et al., 2009). Distinct cycles of varying duration and frequency are present in historical climate records. Identifying each discrete wetting and drying cycle within the record provides information for the final design and function.

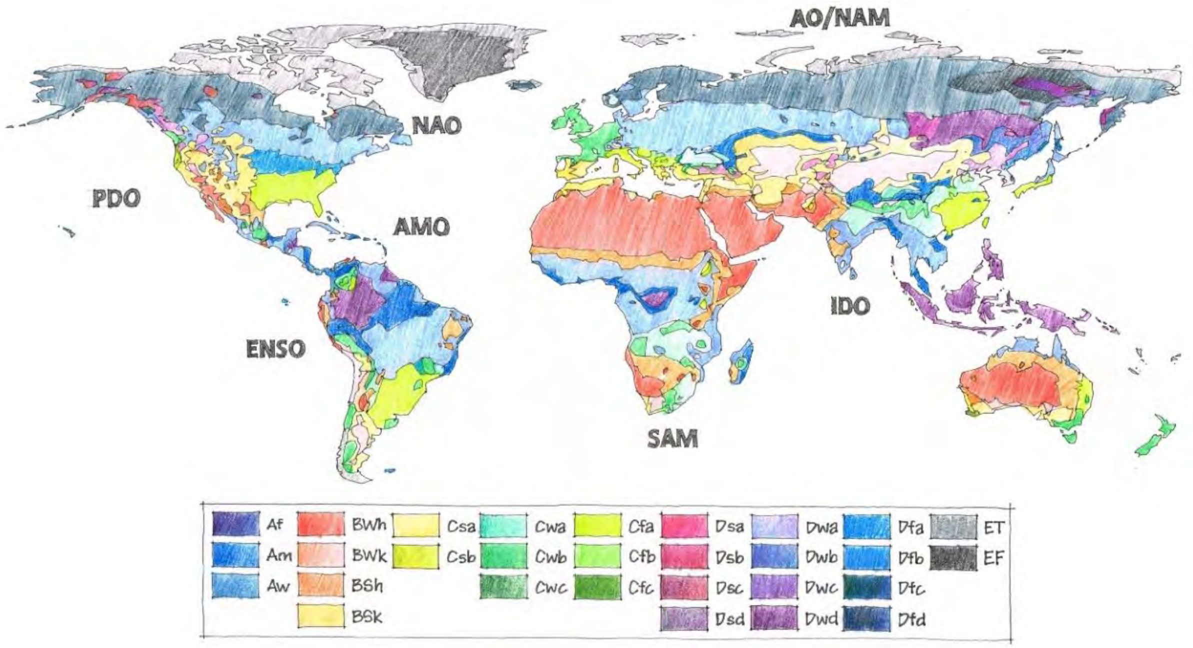

Figure 3-6. Major global dominant climate cycles and region of prevalence overlaid on Köppen climate classification.

An in-phase effect could result in climate extremes (flood or drought) due to mutual strengthening of coinciding amplitudes. Alternatively, “normal” climate may arise from off-phase interactions that cancel each other out. By identifying periods when multiple climate oscillations amplify dry periods or wet periods, planners can better understand how current water management approaches fit into the overall context of the closure timeframe and thus cover system and landform design.

Climate is the ultimate governor of cover system performance at a mine site. While certain cover system design parameters can be adjusted to a degree, the climate at a site cannot be controlled. Therefore, it is imperative that the designer fully understands the dominant climate at a site. All too often a simple average of climate parameters is an input into the models used during the cover system design process. Not only does an average value of precipitation or air temperature result in an unrealistic generalization of conditions, it fails to account for the cycles of variation inherent in all climate signals. Failure to examine the scales of variability within a climate dataset necessarily results in a spurious simplification of a complex system.

Determination of the cycles of variability underscores the importance of understanding where in a wet-dry cycle the system is being designed. If an average precipitation value is used from a dataset that does not capture the dominant scales of variability, the design cannot be fully optimized. For instance, if a 10-year average precipitation value is used to determine the optimal cover system thickness for supporting vegetation, and the average was taken from a dry, or drier, cycle, the system may not be able to support vegetation throughout the entire life of the cover system. Conversely, when designing upland/wetland reclamation systems, it is critical to have a good understanding of long-term climate to ensure the watershed will have enough water supply to support wetland functions. If the watershed designer does not incorporate an analysis of precipitation trends and cycles of variability, the system will be less likely to be resilient to the cyclical changes in water supply.

3.6.2 Climate Change

Climate change refers to a change in the state of the climate that can be identified by changes in the mean and/or variability of its properties over an extended period, typically decades or longer (IPCC, 2014). Climate change excludes fluctuations in climate over periods shorter than a few decades (e.g., El Niño).

Many jurisdictions require some consideration of climate change in closure planning and reclamation. The amount of expected change varies with geography. Where modest changes are expected, cover system designs are robust. In other areas (particularly cold regions) rapid warming trends of past decades are a central consideration. The Intergovernmental Panel on Climate Change (IPCC, 2014) provided a synthesis of future climate change predictions for each region to help planners anticipate long-term trends. When determining the timeframes for landform evolution and closure objectives (e.g., “stable for 100 years”), forecasting a century into the future should coincide with 100-year predictions of climate. Designing for climate change beyond 100 years is fraught with difficulties due to growing degrees of uncertainty (Nordstrom, 2009).

The newest scenario processes in the IPCC’s AR5 synthesis report (IPCC, 2014) are based on regional climate predictions for future Representative Concentration Pathways (RCPs). Four RCPs, expressed as the cumulative measure of human emissions of greenhouse gases from all sources, were selected and defined by their total radiative forcing trajectory and level to 2100. They represent a broad range of climate outcomes and are neither forecasts nor policy recommendations. The scenarios are commonly used as inputs in models of future climate changes.

Regional climate predictions based on RCPs can be used to adjust historic climate databases for a given site so that they account for various RCPs in a stepwise sensitivity analysis. In this way, multiple iterations can be analyzed to produce probability-based distributions of performance (e.g., net percolation) for a given scenario to help managers evaluate risk.

The most pertinent variables for cover system design are temperature and PPT. Future temperature trends and estimates for most regions possess a high degree of confidence, while changes in PPT are more uncertain. For this reason, incorporating climate change into cover system design in cold regions, which can expect the largest changes in climate, will be more important than for designs for equatorial sites. Global circulation models (GCMs) excel at capturing trends in global temperature but are less successful in simulating historical trends and spatial distribution of PPT. Although the models are grossly simplified representations of the global atmosphere, GCMs are nevertheless complex and offer the best tool available to make future projections of where and when temporal distributions and changes are important. In a region characterized by potential annual water deficit and punctuated by periodic surplus, the frequency and magnitude of PPT will have large implications for available water resources.

Applying various climate databases and adjusting those using different RCP scenarios allows designers to model how climate change will affect long-term cover performance. Incorporating climate change into long-term design can be achieved by altering the boundary conditions of the cover system models in a probabilistic way, rather than the more traditional maximum-minimum boundary method. In using a probabilistic evaluation of meeting cover system performance criteria under climate change scenarios, one can incorporate and evaluate an associated risk.

In general, this guidance documents advocate that a “base case” climate database includes the effects of climate change for an agreed upon RCP scenario. The basis for this approach is that, from a cover system and landform design and performance perspective, climate change is occurring, and that the cause and approach to managing climate change are not within the scope of this document. It is suggested that “sensitivity analysis” on climate change then be undertaken by evaluating the “base case” climate database for alternate RCP scenarios.

4 COVER SYSTEM FUNCTIONS AND TYPES

Cover system functions and types span a large range of possibilities. As such, the topics presented within Section 4 provide cover system designers an overview of the key concepts involved with cover system design. However, due to the complexity often involved with not only designing but implementing cover systems throughout the life-of-mine and closure timeframes, additional considerations such as material evolution are important. Further discussion on the following have been included as part of Appendix B:

- Soil salvage;
- Geochemical characterization;
- Geotechnical characterization;
- Near surface density conditions of growth medium layers;
- Material evolution; and
- Material segregation.

4.1 Reactivity of Mining Waste

Sulphide oxidation of mine waste is the critical geochemical issue at many mines, although many other reactions may be present. Identifying if and what geochemical problems exist at a site should be a mandatory first step in the cover system design and management process. This is outlined in Chapter 4 of the *GARD Guide*. In most situations, the contaminant loading principals and conceptual models presented may still be applicable. For other reactive materials, oxidation is a major issue, as is managing NP to prevent mobilization of the constituents of potential concern (COPCs). NP usually leads to flushing of the pore volume, in which the majority of COPCs will be present. It is also important to note, cover systems may be utilized for non-reactive waste storage facilities (e.g., erosion protection).

Demonstrating the role and value of the cover systems in mitigating adverse impacts on receiving environments can be challenging due to:

- Dynamic variations of acidity loading with/without cover systems;
- Difficulty predicting the period in which post-closure costs associated with treatment continue;
- A discount rate for NPV calculations agreed to by all stakeholders; and
- Uncertainties associated with all processes (values) used to estimate pre-closure, closure, and post-closure costs.

Opinions, evidence, and research differ on the benefits a cover system provides in reducing NP. Demonstrating benefits compared with a direct ML/ARD collection/treatment system increases the complexity, particularly when costs are considered using NPV calculations. A conceptual relationship between a specific COPC load and NP for site-specific cover system design alternatives helps make informed management decisions. Mitigation of ML/ARD is therefore discussed in the context of limiting oxygen ingress and NP as the primary design objectives.

4.1.1 Chemical Load Generation

Contaminant load can be calculated as the drainage volume (flow rates or NP) multiplied by the contaminant concentration (e.g., mg/L). From a closure perspective, NP from cover systems often directly controls flow rate from a storage facility into the underlying waste storage facility, once the WSF has completed the process of wetting up and/or draining down. The water carries products from sulphide oxidation (e.g., from oxygen flux through the cover) as well as products associated with secondary acidic salts and neutralization to the receiving environment (generally formed when contaminant load from the WSF is less than the contaminant generation rate due to oxidation processes).

Acid generated by oxidation of sulphides (e.g., pyrite) in waste rock or tailings is well known in the mining industry. Water and oxygen are two reagents associated with sulphide oxidation that contribute to the formation of acidity. Water is also responsible for transport of the generated acidity (ML/ARD) from waste storage facilities. In general, there is sufficient water available to satisfy pyrite oxidation requirements in most waste storage facilities, except for very dry material; however, the concentration and volume of ML/ARD are directly affected by the rate at which water flushes through the reactive material.

Cover system designs should consider whether the objective is to limit oxygen ingress, water ingress, or both. For instance, a historical waste rock dump with a large reservoir of stored acidity might require a cover to limit water ingress (NP) and reduce the load to the receiving environment. Fresh waste rock with low levels of oxidation products, on the other hand, could exclude oxygen and thus the formation of acidity and COPCs. In this case, NP may be of less importance initially as there are minimal COPCs to transport.

4.2 Cover System Function Continuum

Most cover systems are designed to quantitatively manage net percolation, oxygen ingress and/or erosion, but also in terms of downstream water quality and other impacts. The site-specific climate is almost always the strongest determinant of cover system performance as it relates to rates of NP, oxygen and erosion. Climatic effects on NP will have implications for managing both oxygen and erosion and will limit what is ultimately achievable downstream.

This document defines performance for cover systems for each of NP, O_2 ingress, and erosion as a continuum. The continuum represents a continuous sequence in which adjacent performance elements are not perceptibly different from each other, although the extremes are quite distinct. At each extreme end of the continuum, a dominant controlling mechanism is largely responsible for the performance of the cover system (Figure 4-1).

The remainder of this section looks at each of these three main functionalities in more detail.

4.2.1 Net Percolation Function

Cover systems limit NP by one of two methods, representing extreme ends of the NP continuum.

1. **Diversion:** a layer of the cover system may be constructed from materials with a sufficiently low permeability to limit downward percolation of rainfall or snowmelt, and "release" water "outflows" (runoff and interflow).
2. **Store-and-release:** infiltrating water is stored within the rooting zone of the cover, so it can be subsequently released via ET. In these types of cover systems, the objective is to minimize deep percolation by returning most of the infiltrating waters from storage to the atmosphere via transpiration and/or evaporation.

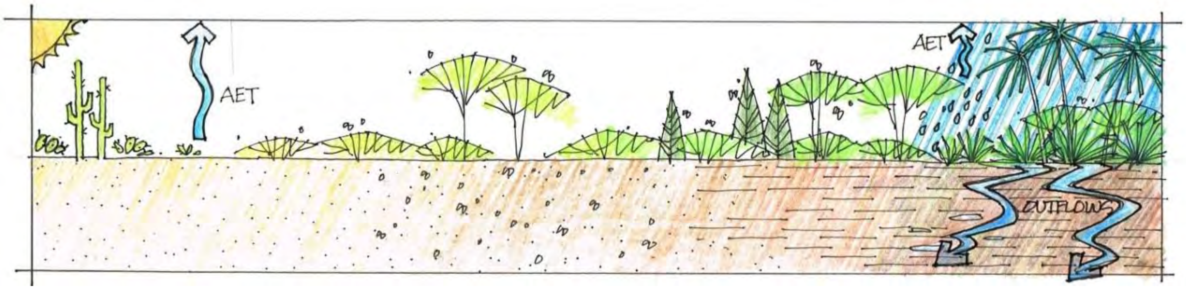

Figure 4-1. Conceptual dominant mechanisms contributing to net percolation based on climatic regime.

Achieving 100% of the function for each end member is impossible. It is more realistic to evaluate these design processes as a continuum of performance, which is a function of climate, hydrogeology, materials, and vegetation. All cover systems provide store-and-release components as well as diversion functionality under specific conditions. Therefore, cover system functionality also occurs along a continuum, with the focus of the "store-and-release extreme" on enhancing storage and ET components of the water balance, while the "diversion extreme" relies on the dominance of runoff and interflow. A store-and-release cover may still possess water-shedding abilities when infiltration excess runoff occurs during high-intensity precipitation. Likewise, cover systems with a focus on water diversion can often possess vegetation, or small amounts of storage, that contribute to ET.

The variability in precipitation during a given year, rather than the annual average PPT, has the greatest influence on NP. The timing, volume, and intensity of precipitation all influence NP. In arid climates, when light rain falls on hot, dry surfaces, a fraction of the PPT evaporates almost instantaneously with another fraction of rainfall is retained on wet surfaces. Following surface wetting, PPT migrates into soil pores under the influence of gravity and capillary suction. Arid and some temperate climates may experience these dry soil conditions for part or all the year and thus NP may largely be managed through evaporation and storage.

Infiltrating water is generally confined to the near surface for arid and semi-arid climates. For uncovered systems, this represents the upper profile of the waste materials, although rapid flow can bypass the soil matrix. For covered systems, generally only the upper cover profiles (i.e., growth medium) are involved. This is caused by lower PPT amounts and extreme soil water deficits. From a contaminant transport perspective, only a portion of the storage facility in semi-arid and arid climates may be transmitting load for much of the time. However, in the event of a breakthrough recharge event, in which storage capacity of the cover system is overwhelmed, an excessive buildup of water in parts of the system, which has otherwise been at residual saturation can occur. During residual water conditions, much of the stored acidity load remains immobile, and with a change in water content, remobilization can occur, effectively transmitting a contaminant "slug" through the system.

If rainfall continues with sufficient intensity, water will begin to fill larger soil pores, infiltrating the soil surface. Depending on the rainfall intensity and soil structure, the flow type can range from unsaturated flow through the soil matrix to channelized flow through open macropores.

4.2.1.1 Store-and-release Mechanisms

Climate influences ET through changes in PET, which in turn is a function of air temperature, wind speed, net radiation, ambient air temperature, and available water in the near surface material. The factors influencing ET are largely site-specific, and age-dependant if vegetation is incorporated.

ET becomes a more dominant mechanism in controlling NP in arid regions and during the summer in temperate regions when there is more available energy. It is less dominant for managing NP in humid regions, as the amount of water involved is substantially lower than with runoff during critical rainfall periods when breakthrough may occur. Nevertheless, ET remains an important mechanism in managing NP for tropical climates due to consistently high annual temperature. In the case of tropical monsoon climates, a long period of hot dry weather may follow months with large volumes of PPT. Although runoff is an important mechanism in managing NP during the monsoon seasons, large amounts of ET are required during the non-rainy periods. ET during non-rainy periods depletes stored water in the cover systems, thereby providing adequate storage capacity within the cover to support evaporation and transpiration drivers prior to the onset of the next period.

For example, at sites where precipitation including snowmelt exceeds ET, either seasonally or annually, the design will need to incorporate components that exploit and/or enhance runoff to manage NP if storage occurs or is expected to be overwhelmed. Conversely, at sites with low PPT, the reliance on promoting runoff is not as paramount, as the ET mechanism can dominate to manage NP.

4.2.1.2 Diversion Mechanisms

The other dominant mechanism for managing NP from a climatic perspective is diversion of water from the cover system, generally as runoff or interflow. Runoff may occur through three primary mechanisms. First, infiltration-excess overland flow where infiltration occurs when the rate of precipitation exceeds the rate at which water can infiltrate the substrate, and any depression storage has already been filled. Contrarily, saturation-excess overland flow occurs where substrate is saturated and depression storage is full; continued rainfall will immediately produce surface runoff.

Antecedent soil water is a key factor affecting the timing and magnitude of runoff in this situation. Finally, subsurface return flow occurs following water infiltration in areas of increased hydraulic head (i.e., up-slope), with the water flowing laterally within the profile to areas of lower hydraulic head. Water may therefore express itself from interflow to surface flow and will be controlled by the hydraulic properties of the material in conjunction with magnitude and intensity of PPT.

If rainfall rates exceed the initial infiltration capacity of the soil, ponding at the surface may develop if mechanisms for effective runoff have not been considered or have failed over time. Alternatively, near-surface storage may be filled completely and any subsequent PPT will report as runoff. This mechanism is particularly common in temperate and tropical climates. In many tropical climates there is a large water surplus and antecedent water conditions are high. Rainfall may exceed evaporative losses on the order of several metres, making it challenging to remove all water as NP. In effect, the evaporation and transpiration components of the water balance are overwhelmed. Moreover, in temperate regions, snowmelt of a winter’s worth of PPT may be released over a few days, resulting in overland flow from slow infiltration or soil saturation. Flow over frozen ground further complicates the water balance.

Although runoff mechanisms may not dominate in arid climates, all cover system types possess the ability to produce runoff, depending on the magnitude and intensity of PPT. Runoff is an important mechanism that may only operate on the order of days to minutes, as is the case with spring freshet or cyclone events, respectively. Even during these brief periods, significant changes to the cover may occur, and rampant erosion in extreme events is possible on many cover systems.

4.2.1.3 Example – Lesson Learned

Achieving NP rates below a threshold of approximately 5% of annual precipitation for both arid and tropical climates is possible, with a reasonable level of confidence, by employing a geomembrane barrier within a cover system. This may imply that climate can be accommodated through a single, rigid and prescriptive design. However, it is important to understand the consequences of a linked performance mechanisms for both oxygen and erosion potential. Although the geomembrane may prove extremely effective in managing NP to underlying materials, the input of water to the cover system remains fixed. The trade-off is therefore partitioning water that was destined to report as NP into either interflow or runoff. Although the geomembrane reduces the cover system design to one of managing NP, caution is required as it leads to a greater potential for erosion, because what water would have reported as NP, is now increasing runoff rates, and thus erosion potential. For most, if not all sites, the difference in a cover system design employing a geomembrane layer would require design specifications for the drainage layer overlying the geomembrane, as well as runoff management, so water can be transmitted laterally from the landform with minimal erosion and disruption of cover system functionality.

4.2.2 Oxygen Ingress

Conceptually, contaminant-loading from a mine waste landform is related to both NP and oxygen ingress. A detailed discussion of gas transport mechanisms is available in the *GARD Guide* (INAP, 2009) and Wels et al. (2003). Much like controlling NP, control of oxygen ingress is a specific design criteria, or the result of another criteria, such as meeting a specific water quality target. Before employing cover systems as a tool to manage the ingress of oxygen to reactive materials, an assessment is required on the plausibility of limiting oxygen to a level that will reduce chemical loadings under site-specific conditions.

Diffusion and advection with flowing air represent the primary mechanisms for oxygen transport across and/or through the cover system (Figure 4-2).

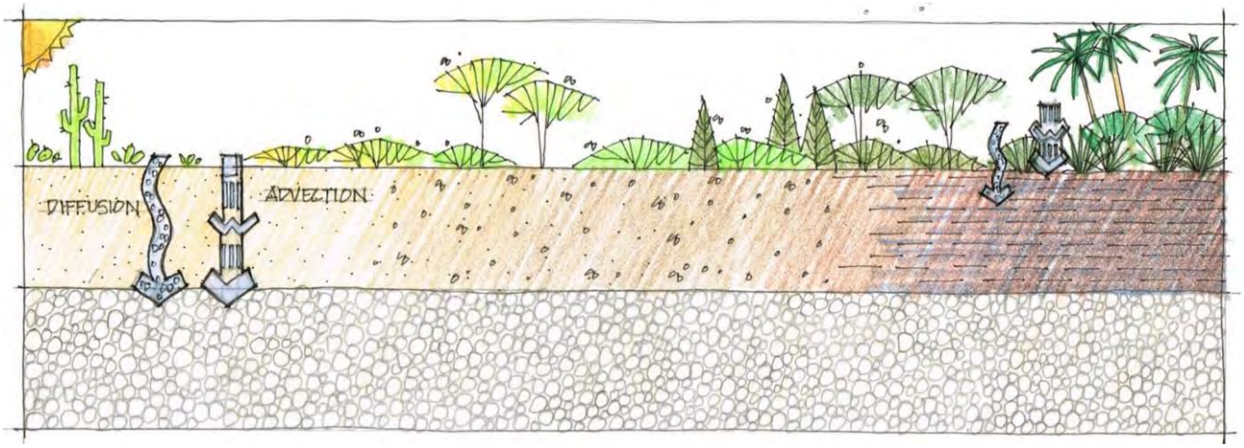

Figure 4-2. Conceptual dominant mechanism contributing to oxygen ingress based on climatic regime.

Oxygen diffusion can be restricted by decreasing the diffusion coefficient of the cover and/or waste, generally by increasing the degree of saturation. Limiting the advective transport of oxygen requires that the cover or waste restrict air flow by reducing pressure and/or thermal gradients, and/or the permeability of the material. It is often easiest to control the permeability of the material through engineering means, and in the case of oxygen, this can often lead to controlling the diffusion coefficient. In the latter case, this is often achieved by creating and sustaining tension-saturated conditions in a layer within the cover system.

Substantial challenges exist when attempting to limit the ingress of oxygen through cover systems, particularly in arid, cold, and most temperate climates. More specifically, advective transport of oxygen will be higher in climates that are generally water-limited due to increases in air permeability. Furthermore, climate dictates temperature controls on advective mechanisms, whereby large changes in ambient temperatures in comparison with internal waste storage temperatures can establish pressure gradients. Provided sufficient air permeability exists, this leads to potentially large advective gas fluxes. The influence of ambient temperature changes on resultant pressure gradients is a function of internal thermal regimes. As outlined in the *GARD Guide*, oxidation of typical reactive material within mine storage facilities is an exothermic reaction; hence, a wide range of temperature conditions can exist within a waste storage facility.

Advective flux of oxygen into waste storage facilities is greater when preferential flow pathways exist due to the increasing conductivity term in the Darcy flux equation. Preferential pathways for advective fluxes can exist in both uncovered and covered storage facilities. Examples of such pathways include:

- Boulder rollout zones;
- Segregation of waste rock material (or heap leach material) during placement in the facility;

- Natural cover system cracking (e.g., freeze-thaw, wetting and drying cycles, and root desiccation);
- Poor cover system construction quality control and assurance; and
- Inadequate subsurface mapping (e.g., tunnels, shafts, subsurface conduits, and water adits).

4.2.2.1 Example – Lesson Learned

Table 4-1 illustrates oxygen flux and acidity load that might develop for a cover constructed to maintain different levels of saturation, including those that use materials with higher water retention characteristics such as a compacted clay layer (CCL) or a near-surface layer within the reactive material.

Table 4-1. Changes of oxygen influx and acidity load against selected saturation conditions of a cover layer (assuming a 150 ha surface area).

Average Saturation Condition of Layer (%)	**Oxygen Influx**		**Acidity Load**	
	($g/m^2/yr$)	**(mol $O_2/m^2/yr$**	**(mol $H_2SO_4/m^2/yr$)**	**(t $CaCO_3$ acid/yr)**
75	~250	~10	~5	~600
80	~125	~5	~2	~300
85	~50	~2	<1	~125
90	~15	<1	<1	~50
95	~2	<0.1	<0.1	~5
100	<1	<0.01	<0.01	<1

- pore space [O_2] = 3%;
- layer thickness is assumed to be 2 m;
- WSF ~150 ha.
- calculated acidity assumes complete reaction of oxygen with pyrite.

In changing the degree of saturation of the engineered layer at the surface of the waste from 80% to 85%, the resulting acidity load decreases by ~55%. Typically, the difference between active treatment and potentially exploring lower-cost passive treatment options is if all this load can be leached from the waste storage facility over time. Theoretical calculations such as these demonstrate that acidity load can be significantly decreased through small increases in the degree of saturation of a layer within a cover system (or a near-surface layer). This can be achieved provided there are adequate materials and an appropriate climatic regime.

Internal material characteristics, such as waste temperature, will alter the calculated acidity loadings in Table 4-1. From a diffusion perspective, sulphide oxidation is a temperature-dependant process, with both chemical and biological oxidation rates decreasing with decreasing temperature (MEND, 1996). Generally, chemical reaction rates double for every 10°C increase in temperature. Although it is important to understand the overarching climatic controls on a material storage facility, chemical, physical, and biological processes differ on a site-by-site basis and should therefore be characterized as such.

4.2.3 Erosion Control and Management

Conceptually, as with NP and O_2, erosion potential is part of a cover system continuum of functionality. Generally, cover system erosion potential is controlled by preventing the discharge of ponded water over crests, reducing surface water velocity in bare areas, and concentrating flows due to topographic constraints. This can be achieved by managing:

- Material texture;
- Slope length;
- Slope angle; and
- Vegetation cover.

Resistance to erosion is an important consideration of cover system design for both reactive and non-reactive waste, with all the above working simultaneously to produce a unique potential erosion risk. Erosion management should aim to achieve the same erosion potential across the entire landform. Due to differences in water balance, energy regimes, and topography across a landform, multiple strategies may be needed to prevent differential erosion rates. The sediment loss from a cover system not only compromises the immediate performance as it corresponds to the ability to manage NP and O_2, but it can also inhibit plant growth after construction. At many mines, growth medium may be a scarce resource, its loss representing a cost and performance risk (e.g., compromising future vegetation establishment). Furthermore, erosion typically results in surface quality concerns due to sediment transport, but also blockage of surface water channels due to sediment deposition.

Immediately following construction, potential erosion risk can be high due to the lack of vegetation, even where rapidly establishing vegetation is used, if revegetation is part of long-term erosion control. Temporary erosion control may be necessary, or at least anticipated in design, in the form of mulch cover systems or seeding with vigorous nurse crops, while slower-growing native species establish.

Special considerations for cold regions can be found in Section 2.2.3 (Erosion and Slope Stability) of the *Cold Regions Cover System Design Technical Guidance Document* (MEND, 2012). Rapid establishment of vegetation can often be more difficult in colder climates, placing more emphasis on material selection and landform design. Arid climates pose their own challenges due to water limitations for supporting vegetation growth.

If a reliance on vegetation cannot be used to provide long-term erosion protection — a likely scenario for many mine sites — other aspects of the cover system design must be manipulated to create a stable landform with acceptable mass loss (Figure 4-3).

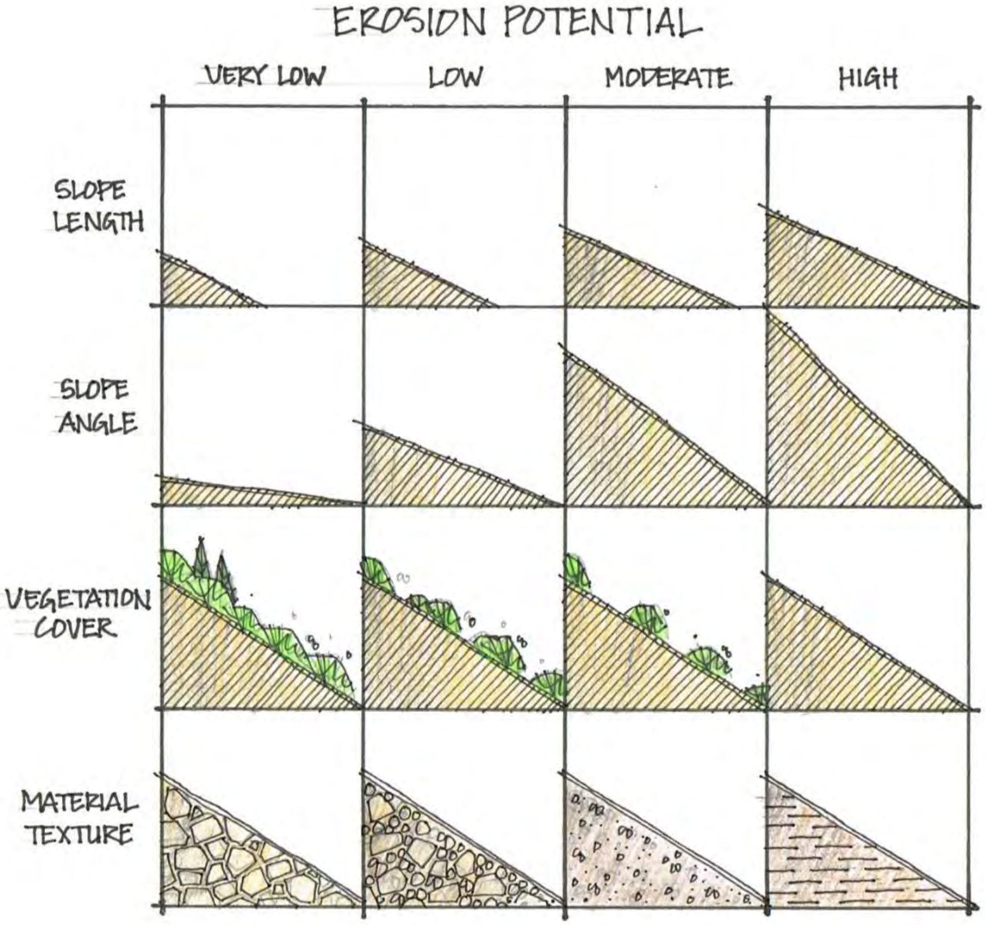

Figure 4-3. Potential erosion control mechanisms for cover system design.

Erosion potential generally increases with greater slope length or angle, finer-textured material and decreasing vegetation cover, although rocky slopes can be more stable. By manipulating these parameters, cover systems can be constructed with increased physical stability even in the absence of vegetation.

A dynamic relationship between material texture and climate manifests in erosion potential of cover systems, and climate classification can be used as a general indication of both vegetation establishment and timing of precipitation. Sites where PPT exceeds PET generally represent easier establishment of vegetation, holding all other variables constant, as compared with arid sites, which are characterized by large water deficits.

Across the spectrum of climates, from arid environments with little PPT to tropical regions with large PPT, erosion potential is minimized at either end after vegetation is established (Figure 4-4). For tropical sites with sufficient PPT, the increased PPT can support denser vegetation cover, thus minimizing erosion potential. By contrast, many sites may produce PPT insufficient for vegetation growth, but what PPT there is of sufficient intensity can still erode cover system surfaces. PPT may lead to poor development of vegetation and thus minimal erosion protection because of the timing, magnitude or intensity of the PPT.

This is an important factor because, in many cases, arid regions are subject to high-intensity precipitation, leading to greater erosion potential. Furthermore, without the ability to rely on vegetation to provide erosion protection, other elements of the design must be utilized to lower erosion potential to meet performance criteria. If the cover system cannot minimize erosion using surface water management features and/or vegetation, the design will need to include additional material for anticipated material quantities lost through erosion to meet long-term performance expectations for oxygen and/or water ingress.

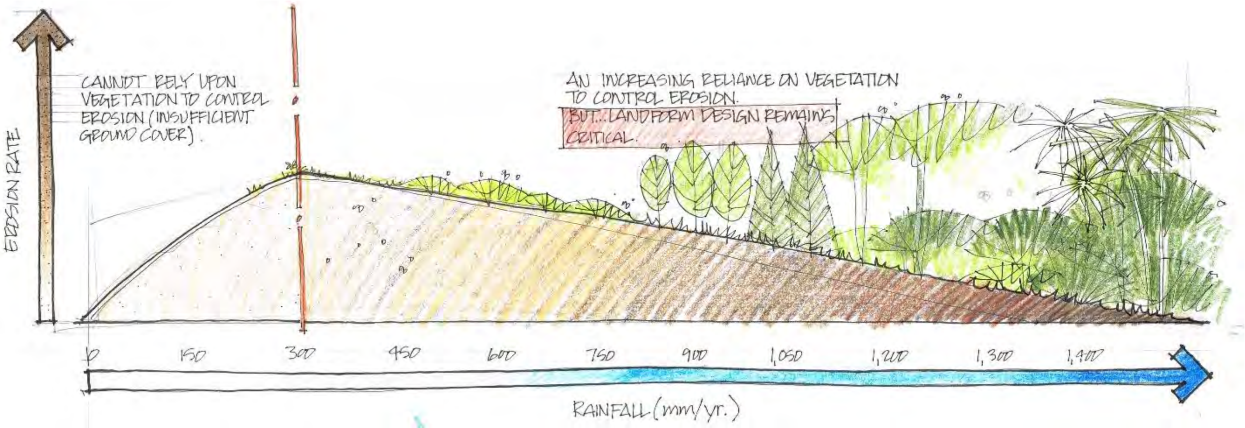

Figure 4-4. Continuum of erosion potential in the context of a climate-vegetation relationship (Marshall, 1973).

Additional permanent erosion control measures can be used in conjunction with introducing vegetation, such as proper grading of contours, berms, swales, diversion ditches, and rock armouring (Norman et al., 1997). Surface water management structures will be needed to prevent formation of erosion features, including:

- Interrill and rill erosion;
- Gully erosion;
- Stream channel erosion; and
- Mass wasting and debris flows.

Erosion predictions, especially for mine reclamation, typically have large "error bars". Erosion rate predictions are generally only accurate to within about an order of magnitude (Trimble and Crosson, 2000). Much of the erosion occurs by rill and especially gully erosion whereas most of the models can only actually handle interrill and sheet erosion. Modelling of erosion rates can still provide insights and sensitivities and use of landform evolution software such as SIBERIA (Willgoose, 2000; Willgoose et al., 1991) can be useful as a design tool and for demonstration; the predicted erosions rates should be used with caution.

4.3 Conceptual Acidity Generating Models

The mining industry is often faced with choosing between ML/ARD management strategies that use active or passive treatment techniques, and prevention/minimization with cover systems (often with reduced volumes to manage). Two conceptual models for contaminant load generation exist when considering management of ML/ARD using cover systems.

4.3.1 Constant Concentration Model

The Constant Concentration Model assumes load increases linearly with increasing NP. Given that: Load = [Solute Concentration (mg/L)] x Flow (i.e., NP (L/s)), the Constant Concentration Model results in a constant solute concentration in ML/ARD, independent of NP (Concentration 1 in Figure 4-5).

The Constant Concentration Model can represent two situations in which the storage facility contains acidic oxidation products that are flushed out with increasing NP, resulting in constant concentration (due to solubility constraints). Where significant secondary acidic oxidation products exist, NP rates must be reduced to control loading rates. Oxygen ingress may also have to be managed to control ML/ARD in the longer term and should be considered.

4.3.2 Constant Load Model

The Constant Load Model assumes a constant load with increasing NP. Although not explicitly depicted in Figure 4-6, it is important to note that the Constant Load Model must have the load equal zero when the NP rate is zero. Therefore, the Constant Load Model assumes a "jump" to a high load occurs with very little net percolation. The Constant Load Model assumes very low NP will result in very high concentration, while high values of NP will contribute to very low concentrations due to dilution (Concentration 2 in Figure 4-5).

The Constant Load Model represents a storage facility where the load is constant with increasing NP. In this situation, sulphide oxidation rates are low — and considerably lower than NP rates — such that increased flow through the facility dilutes the available load associated with acidic oxidation products. Several troubling inferences are associated with this model. For example, even if NP can be reduced to an infinitesimal rate, this conceptual model still dictates the entire load available within the waste material will be transported within that drop of water. In reality, a lower threshold of NP at which the potential load cannot be flushed must exist. Similar conceptual models apply to the effect of oxygen on chemical load generation.

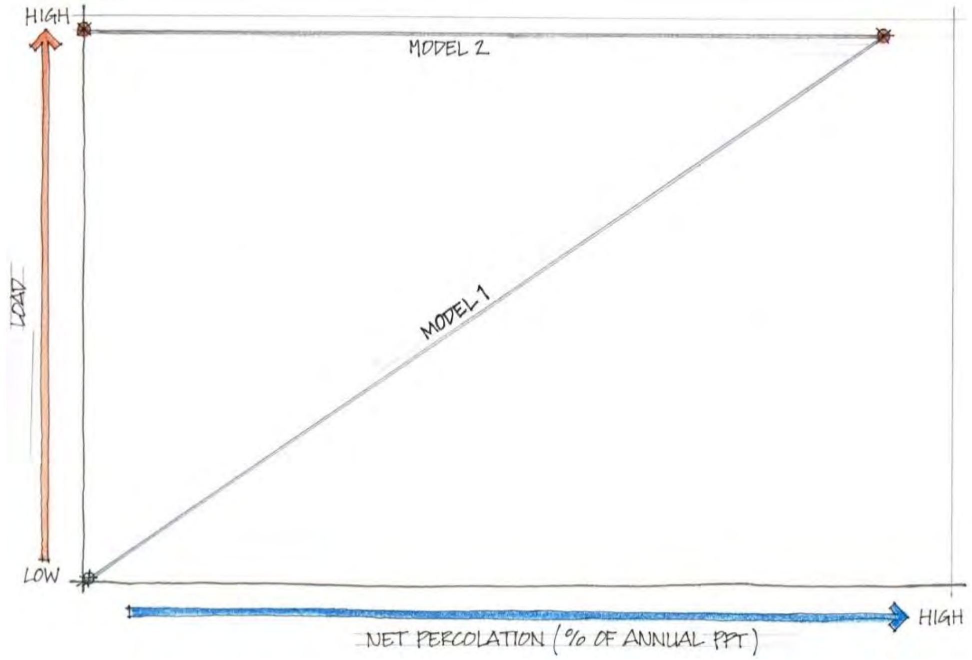

Figure 4-5. Acid concentration and net percolation relationship resulting from conceptual models.

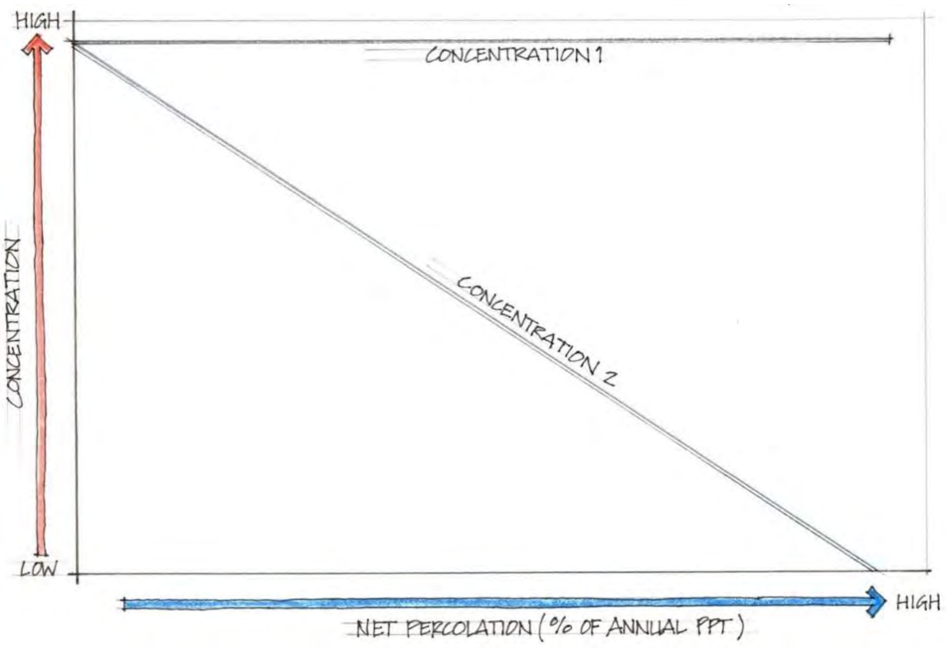

Figure 4-6. Conventional conceptual models showing the relationship between acidity load and net percolation.

In waste rock dumps, it is likely that the mass loading will be due to some combination of solubility control (Constant Concentration) and kinetic control (Constant Load). For example, early mass release may be dominated by pre-existing weathering products (solubility control) followed by a longer-term kinetic controlled release, which could be due to the oxidation rate of sulphides. Understanding the models, or any transition between the models, is important for cover system design and managing loads from waste rock facilities.

The waste storage facility system can be a complex interaction of waste material geochemistry, internal pore-gas conditions, and boundary layer climatic conditions. For waste storage facilities with a given NP, one site with significant stored oxidation products could have a high load compared with another that rapidly excludes oxygen to the sulphide-bearing overburden and where the rock has a low quantity of sulphide oxidation products and low ongoing sulphide-oxidation rates. Therefore, it is not a question of whether the waste storage facility exhibits one specific model behaviour; rather, it is a question of when reactive material switches from a problem to be solved by employing cover systems managing a solubility control to one managing a kinetic control. The importance of cover system placement timing is an integral component of cover system design, as it will help identify the dominant mechanism contributing to load.

4.4 Cover System Design Alternatives

To meet the chemical, physical, and land use objectives described in Section 3.1, various cover system designs may be employed. This section briefly outlines the options and describes their benefits and applicability for use globally. Much of the information can also be found in the *Cold Regions Cover System Guidance Document* (MEND, 2012); the information is included here for clarity of subsequent discussions in this document.

For the purposes of describing the appropriate cover systems, the designs have been divided into the following six categories:

1. Simple-protection cover systems (e.g., reclamation, re-vegetation, isolation, erosion protection cover systems);
2. Store-and-release cover systems;
3. Enhanced store-and-release cover systems (e.g., enhanced with a lower permeability layer, a capillary break, and/or an engineered seasonally frozen capillary break diversion (SFCBD));
4. Barrier-type cover systems (e.g., compacted soil or permanently frozen layer);
5. Cover systems with engineered layers (e.g., geosynthetic layers); and
6. Saturated soil or rock cover systems.

A particular cover system may fall into more than one category. For example, all cover systems provide a degree of erosion protection, and a system with a growth medium overlying a geomembrane can also serve as a store-and-release cover system. A cover system should be evaluated on a continuum of performance values, with differing dominant mechanisms achieving design criteria depending on the unique set of conditions of a site.

4.4.1 Reclamation/Revegetation Cover System

The objectives for reclamation, sometimes referred to as revegetation cover systems, are dictated by stakeholder requirements for final land use objectives. Objectives may include but not be limited to:

- Creation of wildlife habitat;
- Restoration of native plant species;
- Aesthetically pleasing for community and/or stakeholders;
- Provide recreational spaces; and
- Agriculture opportunities.

Reclamation cover systems require the final land use to be identified in consultation with stakeholder groups. The required use will influence vegetation species selection and any specific habitat elements to be incorporated into the cover system design. If the restored native species habitats are to serve as natural analogues, it will be necessary to identify major mechanisms and components of natural adjacent systems. In some cases, a lack of vegetation establishment may be an explicit cover system or closure objective due to technical and/or stakeholder objectives.

4.4.2 Isolation Cover System

Isolation cover systems are designed with the sole purpose of isolating waste from the receiving environment (flora, fauna, and human). Isolation cover systems are employed to prevent migration of constituents of potential concern from the waste storage facilities to environmental receptors. Such system designs must consider vegetation that may grow on the cover system with roots penetrating deeper through time (Figure 4-7). Unsaturated zone hydrology is an important consideration in isolation cover systems as most COPCs migrate due to capillarity within the soil matrix.

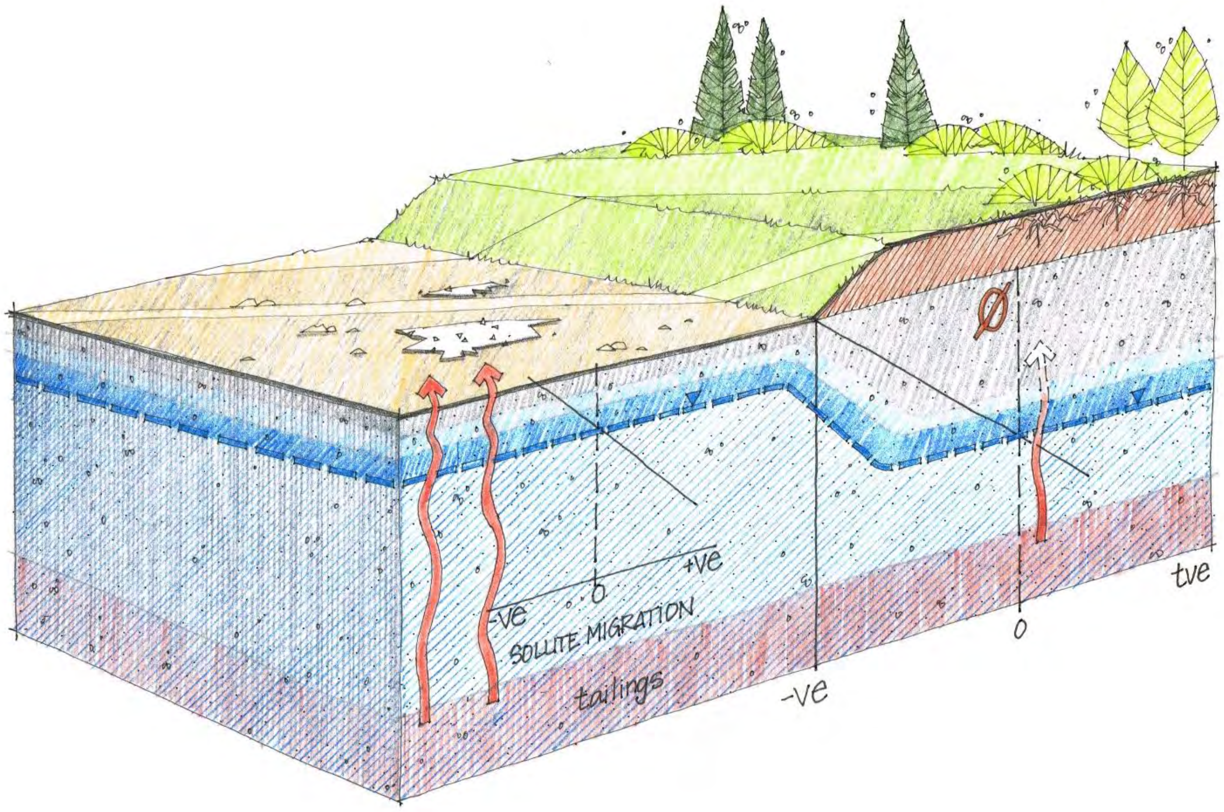

Figure 4-7. Isolation cover system.

4.4.3 Erosion-Protection Cover Systems

The only closure objectives at some sites may be dust control and erosion protection. In these cases, material is typically non-reactive (or management of net percolation and subsequent facility seepage is not an objective) and the goal is to develop a stable landform (from a geomorphic perspective). An erosion-protection cover system refers to protection of the landform and cover system from erosion as well as major components of surface-water management systems, such as drainage channels. An example of an erosion-protection cover system is shown Figure 4-8.

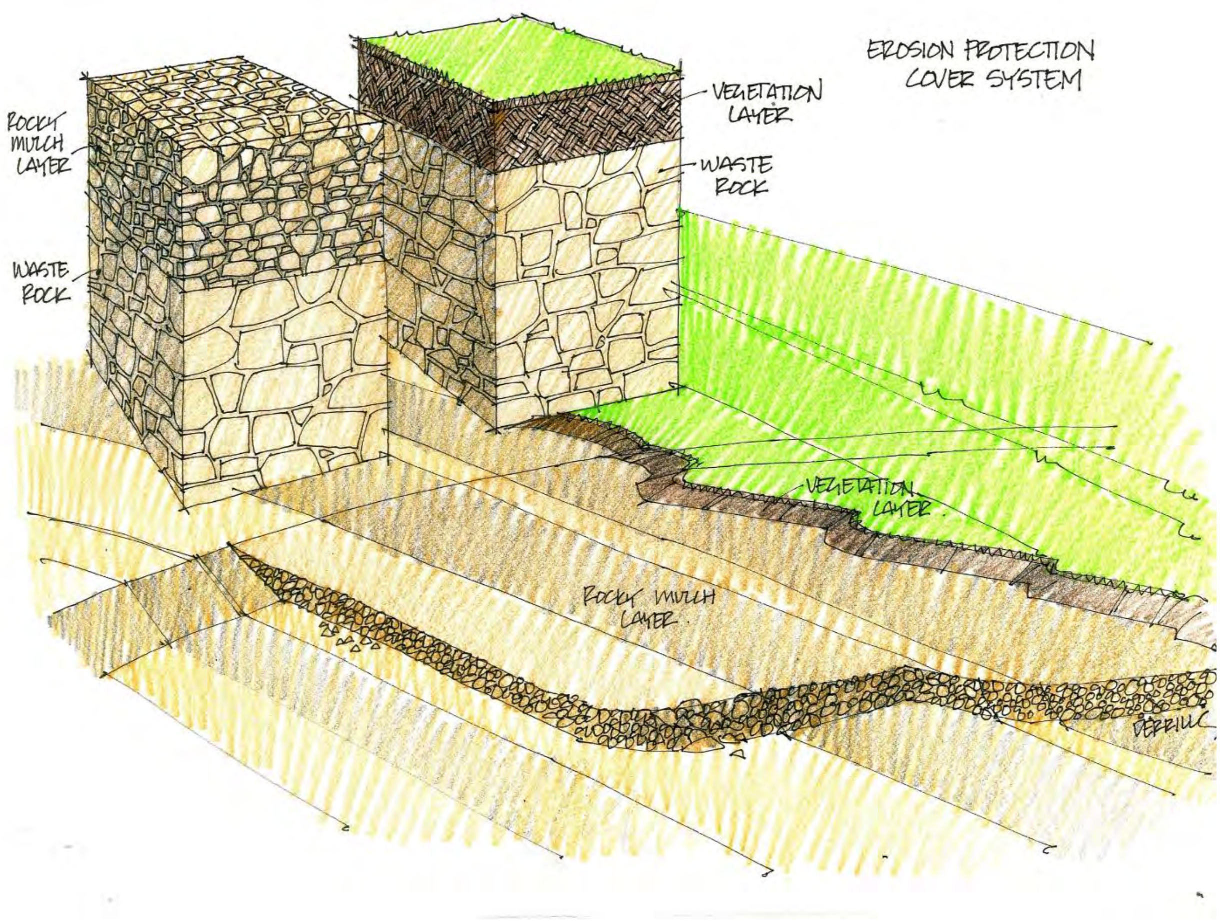

Figure 4-8. Erosion protection cover system.

The vegetation approach to erosion protection involves rapid establishment of a vegetative cover over material to minimize erosion. The material is typically non-reactive and contaminant uptake by vegetation should be minimal. The material (with or without a surface soil amendment) must also have sufficient water-holding capacity to support vegetation growth. Site preparation and vegetation treatments must be conducted to ensure rapid vegetation establishment to minimize erosion.

Additionally, in some instances the vegetative approach to erosion protection maybe too costly, or laden with risk. In these instances, the material must be sufficiently coarse-textured to withstand erosion without additional amendments. While this approach is simple in concept, it can be challenging to implement at a commercial scale. For example, rock with appropriate durability and/or geochemical characteristics may not be available through the site's mine plan, or available at the appropriate time. Hence, caution is warranted before making a "promise" for a "rock cover", which can be costly to implement at closure. For example, rock mulches are an alternative for these types of landforms, because they follow geomorphic principles. Quarrying, crushing, and/or screening may be required to produce such a cover.

4.4.4 Store-and-Release Cover Systems

The suitability of cover systems that rely on the water store-and-release concept to control net percolation will depend on site-specific climate conditions, material availability and characteristics, and the required performance criteria. Figure 4-9 illustrates a generic store-and-release cover system: water infiltrates during periods of high PPT or spring melt and infiltrated water is then stored within the cover until atmospheric and biotic demands can remove the water through evaporation and transpiration.

Material availability and characteristics are significant design elements for any cover system but are of importance for a store-and-release system that relies entirely on the hydraulic characteristics of the materials. To create conditions favourable to a store-and-release cover system, the fines content can be increased by mixing finer-textured material into available coarser-textured materials.

4.4.5 Enhanced Store-and-Release Cover Systems

An enhanced store-and-release cover utilizes the store-and-release concept to meet most cover system objectives but includes additional layers that result in a textural discontinuity. The typical objective is to further reduce NP during relatively short-duration seasonal events when the storage capacity of a store-and-release cover system might be exceeded. Layering can also be introduced to enhance water retention in an overlying layer to be used for root development. Enhanced store-and-release cover systems differ from barrier-type cover systems in that the permeability of the additional layers only needs to be sufficiently reduced to reduce NP to the design criteria, which otherwise would not have been achievable through a store-and-release type cover. Hence, this additional layer is not thought of as a "barrier layer" throughout the year.

Enhanced water diversion provided may not be required for the entire life of the cover system. The enhancement to limit NP could be required only until mature vegetation establishes and the "extra" evapotranspirative capacity of the store-and-release layer begins to function.

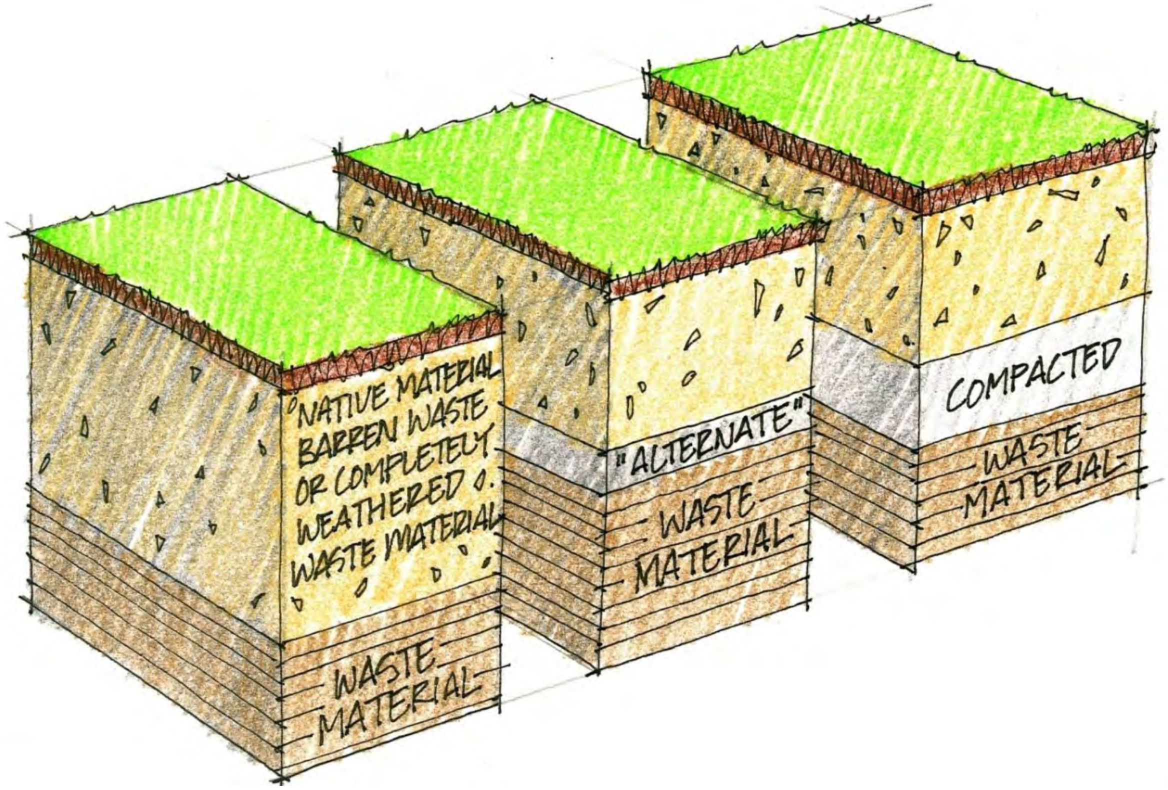

Figure 4-9. Store-and-release cover systems: (a) basic store-and-release cover system, (b) and (c) enhanced store-and-release cover systems showing additional lower hydraulic conductivity layers below the storage layer.

As previously discussed, the addition of a low permeability layer beneath a non-compacted layer may be included in other cover types. Lower permeability layers retard downward percolation. They can consist of weathered surficial waste rock compacted by haul truck traffic or locally available silt/clay deposits that have been mechanically compacted.

4.4.5.1 Capillary Break Layer

A cover system that utilizes the capillary barrier concept is simply another form of an enhanced store-and-release cover system. In short, the development of a capillary break relies on the contrasting hydraulic properties of both the coarser- and finer-textured materials. A coarser-textured layer within a homogeneous, and underlying, finer-textured profile will produce a marked decrease in suction (an increase in negative pore-water pressure) within the coarser layer. The lower suction allows the overlying finer-textured soil layer to maintain a higher water content than that expected for a homogeneous soil profile (i.e., greater than field capacity). Therefore, more water can be held in the upper cover profile, and then evaporated, than if a capillary break was not present.

4.4.5.2 Seasonality Frozen Capillary Break Diversion (SFCBD)

Observations of natural sites in cold regions have established that snowmelt waters can be diverted downslope as lateral flow within a shallow active layer overlying a deeper frozen soil zone (Hayashi et al., 2003, and Carey and Woo, 2001). The impermeable frozen zone can persist long after snowmelt is over, melting only when the thermal conditions of the cover system allow. Impermeable frozen layers often occur when coarser-textured upper layers are maintained at lower water contents. Consequently, the upper layer thaws relatively rapidly each spring in contrast to the lower soil layer at a higher water content (Figure 4-10).

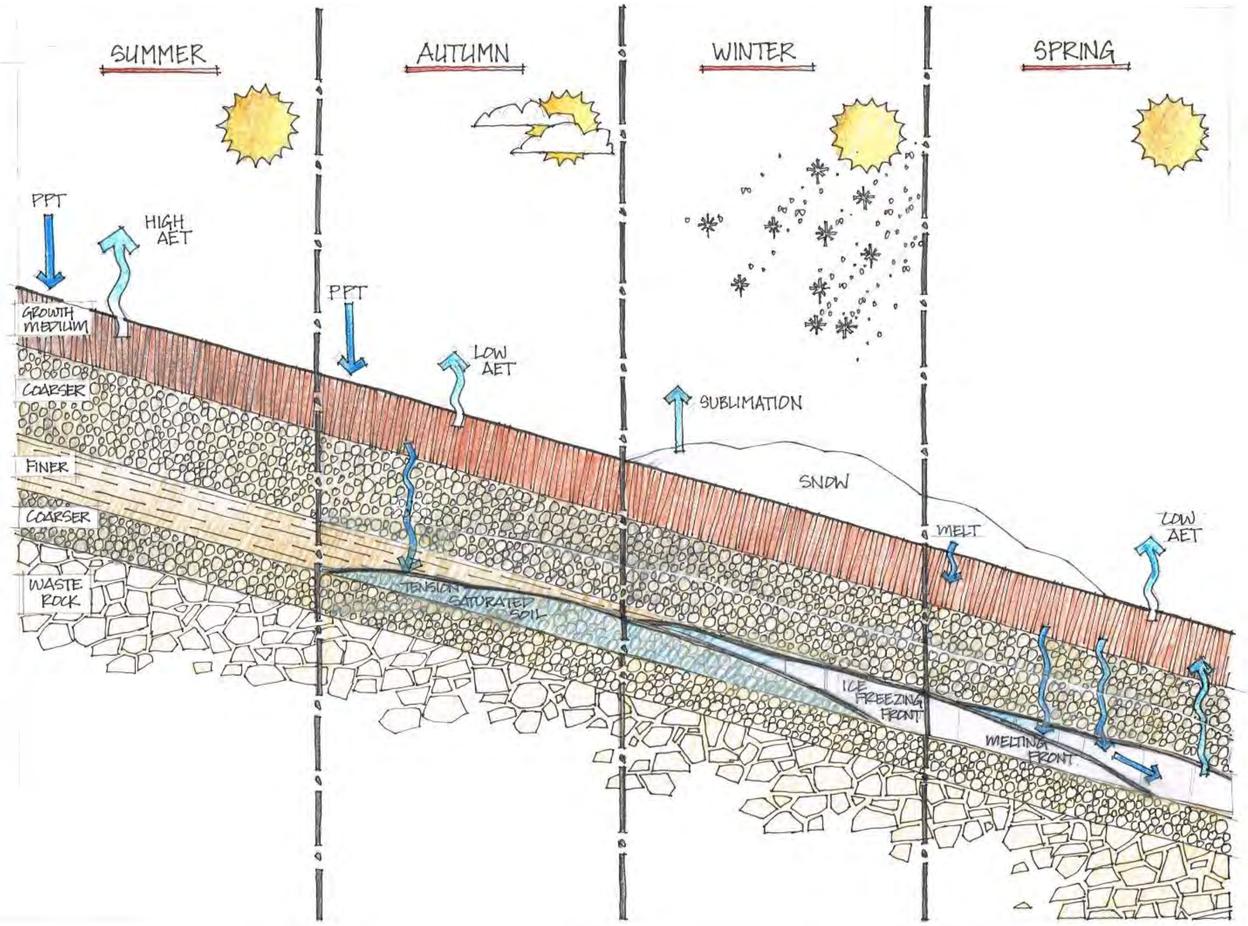

Figure 4-10. Seasonally frozen capillary break diversion (SFCBD) cover system.

This natural process indicates that it is possible to create an engineered layered system in which a surficial, well-drained, active layer is formed over a lower, higher water content layer that remains frozen for a longer period than the layer above. This lower layer may have elevated water contents because it is finer, and/or it is overlying relatively coarser-textured soil. The layered system will result in an increased storage capacity in the upper soil for water that may be removed from the system laterally as interflow, on the surface by runoff, or by vegetation. Once the deeper frozen layer eventually thaws, the increased vegetation and seasonal climate conditions allow the layers to act as a store-and-release cover system for the remainder of the summer.

4.4.6 Barrier-Type Cover Systems

Barrier-type cover systems incorporate one or more low hydraulic conductivity layers to control the ingress of atmospheric water and in some cases, atmospheric oxygen. In the context of this guidance document "barrier" cover systems have a layer with an as-built (field) saturated hydraulic conductivity of 1 x 10^{-7} cm/s, or lower (Figure 4-11). Barrier layer types include compacted clay, compacted sand-bentonite, and a permanently frozen layer. A cover system incorporating a geosynthetic or geomembrane material is also a form of barrier-type cover system, which is summarized in Section 4.4.7.

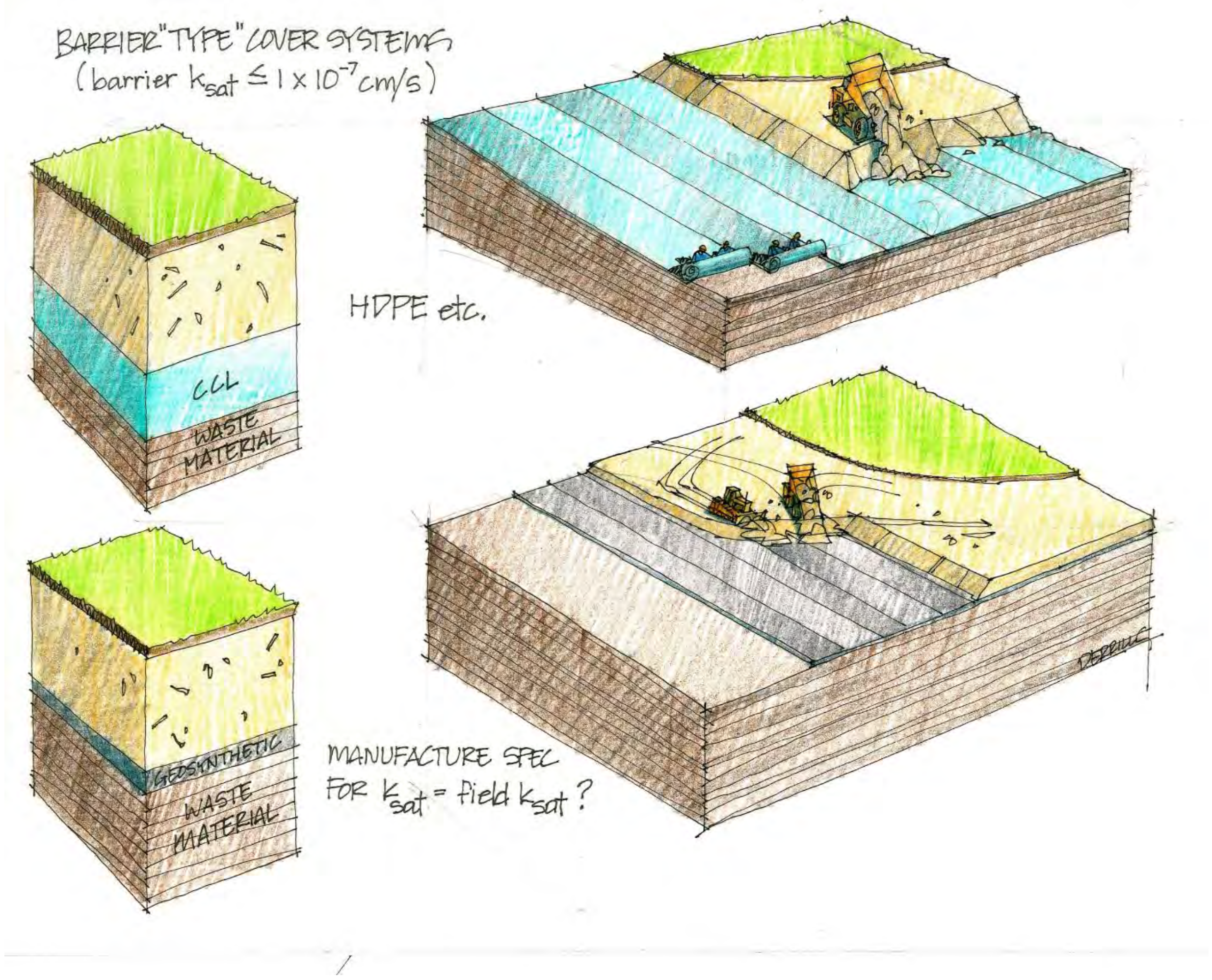

Figure 4-11. Barrier cover systems can decrease hydraulic or air permeability to acceptable levels.

4.4.6.1 Compacted Clay Layer (CCL)

CCLs used in mine cover systems generally range between 30 and 50 cm thick and are typically constructed in lifts ranging in thickness from 15 to 25 cm. Specific lift thickness is dependent on soil characteristics, compaction equipment employed, and strength of underlying materials. Generally, the preference is for thinner lifts due to the ability to impart more energy per unit volume of soil. In this way, thin lifts allow compacting energy to reach the base of the lift.

Important considerations for cover systems employing CCLs include but are not limited to:

- Moulding water content;
- Dry density;
- Borrow material variability;
- Freeze-thaw cycling;
- Wetting and drying cycling desiccation;
- Clay mineralogy compatibility; and
- Root penetration.

Field compaction trials are recommended prior to commencing full-scale construction of a CCL to ensure that the two important elements — density and water content — are present throughout construction. The trials can also help optimize equipment selected for construction and identify unforeseen construction issues. If applicable, field trials should be conducted on both horizontal and sloping areas. Finally, compaction field trials provide an opportunity to evaluate and calibrate quality control testing equipment (e.g., a nuclear densometer) prior to the start of CCL construction.

4.4.6.2 Compacted Sand Bentonite (CSB)

In circumstances where a cover system requires a water infiltration barrier, but no appropriate finer-textured materials are available, a barrier can be constructed by combining available sand (or sandy material) with bentonite (Chapuis, 2002; Chapuis, 1990). Sodium bentonite is generally preferred over calcium bentonite because of its superior swelling capacity and lower hydraulic conductivity to water (Alther, 1987).

The hydraulic conductivity of CSB depends on several factors, including:

- Quality of bentonite;
- Bentonite content;
- Particle size distribution of the host material;

- Degree of blending bentonite into the host material;
- Moulding water content; and
- Level of compaction.

A CSB barrier layer has similar issues to a CCL, and while generally not recommended for cold climates, research does indicate some capacity for a CSB to “self-heal” following freeze-thaw and/or wet-dry desiccation. However, reliance on this aspect of CSBs represents a risk that must be evaluated on a site-specific basis. Chemical compatibility with the overlying cover soil, the underlying material, and infiltrating water must be confirmed to prevent cation exchange with the bentonite (Haug et al., 1988).

4.4.6.3 Permanent Frozen Layer (or Permafrost Aggradation Layer)

As described for the seasonally frozen capillary break diversion cover system, the infiltration capacity is three to five orders of magnitude less for a frozen material than for the same material in an unfrozen state. It is possible to take advantage of this phenomenon in permafrost zones by using the frozen material as a barrier. The cover material would contain the entire active layer, and a zone of permanently frozen ground (permafrost) would develop at the base of the seasonally frozen cover and progress downward. If the frozen material stays at a sufficiently high water content, it could be used as a barrier (Figure 4-12). However, it should be noted that wetter materials take much longer to freeze than dry ones, so any saturated layer at depth will considerably slow the descent of the freezing front on an annual basis.

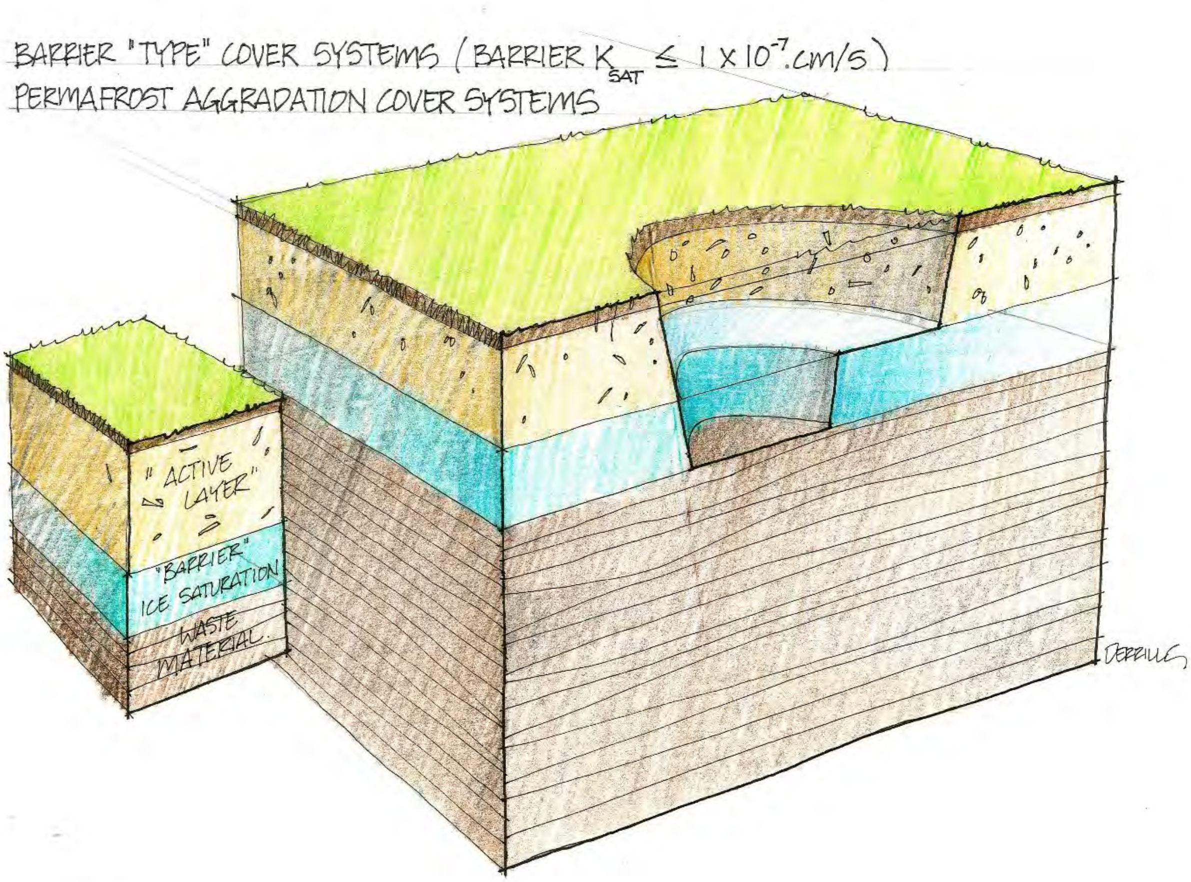

Figure 4-12. Permanently frozen (permafrost aggradation) barrier layer cover system.

The creation of a permanently frozen barrier layer within the waste itself requires that steps be taken to ensure that frozen conditions can be maintained, and that the waste is at a sufficiently high degree of saturation to ensure low hydraulic conductivity. The barrier layer must remain below the active zone to maintain the reduced infiltration capacity for the required operating life of the cover system. The time required to develop permanent ground frost in deep thawed waste may be significant and alternative means of control may be required in the interim.

In many cases, the concept of development of a permanently frozen barrier cover is put forth based on convective cooling of the frozen layer over time. However, caution is required with the efficacy of convective cooling if the underlying waste material is a source of heat (i.e., resulting from exothermic sulphide oxidation and rise of heat within the facility to the surface). As with a basic premise of this entire Guidance Document, deeper conceptualization, or front end load engineering, is advocated to ensure concepts and designs developed at the beginning of the mine life, can actually be relied upon at closure.

4.4.7 Cover Systems with Geosynthetic Materials

The use of geosynthetic materials within cover systems can dramatically reduce NP of water and oxygen ingress. Inclusion of a geosynthetic material or geomembrane as part of a cover system design is often required if the performance objective of a cover system for a site in a wetter climate includes achieving very low NP rates (e.g., <5% of PPT). Reductions of up to <1% of PPT is possible but requires a recognition that geosynthetic products have a serviceable lifespan. When rates as low as 1% are a design objective, the risks must be managed through routine inspection and replacement according to manufacturer specifications. In addition, achieving very low net percolation rates consistently, and over time, will require appropriate focus and design in the lateral diversion capacity of the material above the liner. With appropriate lateral diversion capacity, the inevitable development of holes, tears, defects, degradation, etc. of the geosynthetic layer may not necessarily result in substantial increase in NP.

Available geosynthetic materials used in cover systems include:

- Polypropylene (PP);
- Chlorinated polyethylene (CPE);
- Polyvinyl chloride (PVC);
- Linear low-density polyethylene (LLDPE);
- High-density polyethylene (HDPE);
- Geosynthetic clay liners (GCLs); and
- Bituminous geomembranes (BGMs).

Within each of the above classifications of geosynthetic materials, there is a spectrum of products available, which should be selected based on site-specific conditions and performance considerations (Figure 4-13). Most geosynthetics are subject to degradation by sunlight, physical penetration, or damage (including vandalism) and must be protected with an overlying earthen cover material. If one of the cover system objectives is to establish vegetation, then an overlying earthen layer suitable to this purpose must be included. A protective or growth medium layer above a geomembrane is at additional risk of solifluction on slopes due to the relatively impervious nature of the liner (hence increased water contents and pore-water pressures within the cover above the liner) and the potentially lower friction angle of the geosynthetic material. Before placing a geosynthetic liner, the surface of the underlying material must be carefully and uniformly prepared to manufacturer's specifications. Generally, prior to preparation, the surface may cause damage to the geomembrane.

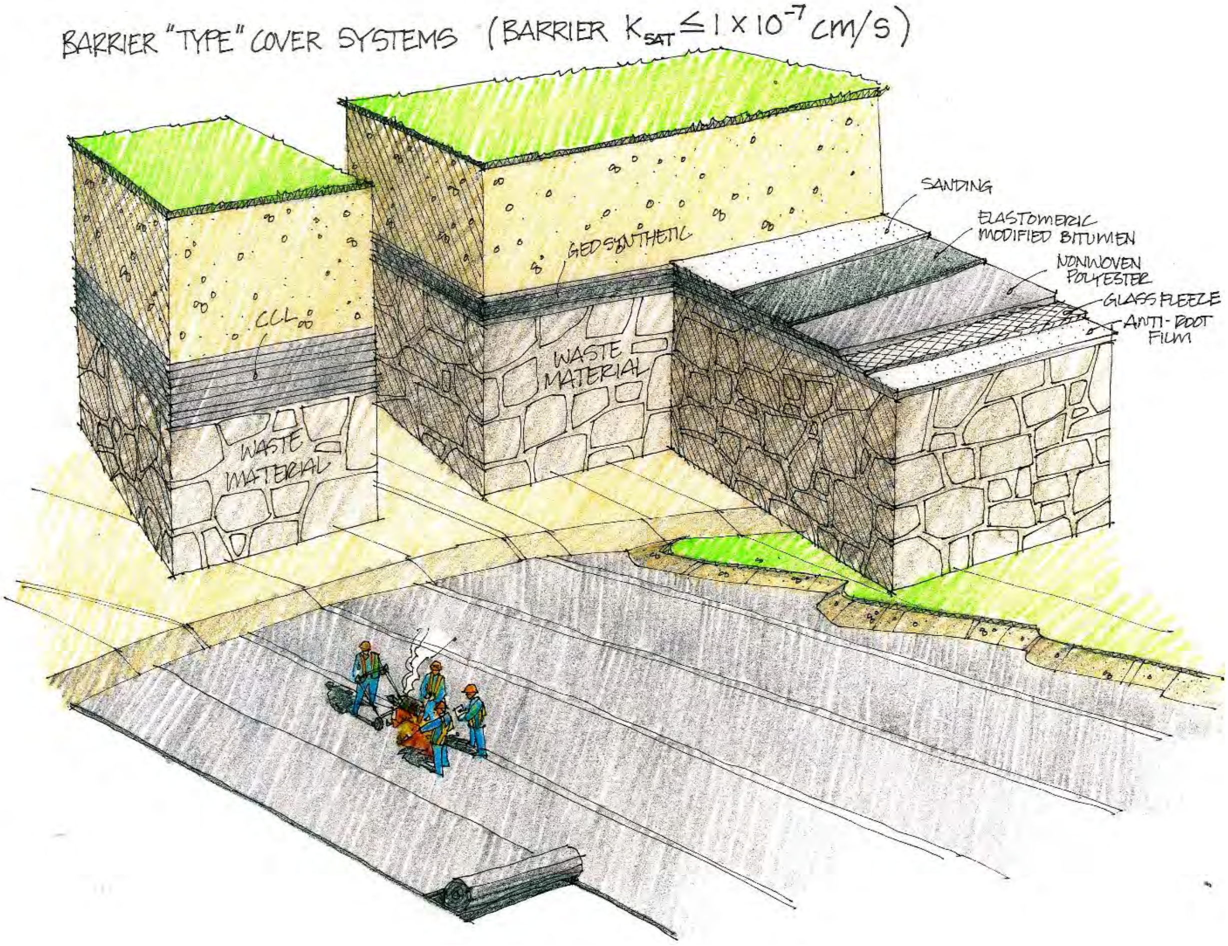

Figure 4-13. Barrier-type cover systems employing a CCL or BGM to decrease hydraulic or air permeability to acceptable levels.

4.4.8 Saturated Soil or Rock Cover Systems

Disposal of reactive materials below a water cover (Figure 4-14) is an extremely effective method for limiting sulphide oxidation due to the large reduction in oxygen availability. However, with the proper conditions and careful design, it is possible to create saturated material deposits that are effectively "water-covered" without open water. This type of approach has the potential for greater longevity than other closure solutions given.

The objective of a saturated cover is to cover the reactive material with a layer of water to restrict oxidation and acid generation. The key design consideration is to raise the water table, also known as the phreatic surface, above the contaminated material by placing an inert material, usually coarser-textured material, as a cover and maintain the water table within this layer. The water table can fluctuate within the coarser-textured material, but the cover should be designed so that the risk of the water table falling below the surface of the material to be isolated is managed, as is the risk of the water table breaching the surface and expressed as standing water. The water table is often controlled within the inert layer using a spillway, or some variant, with input provided from groundwater, surface water, and/or surface infiltration.

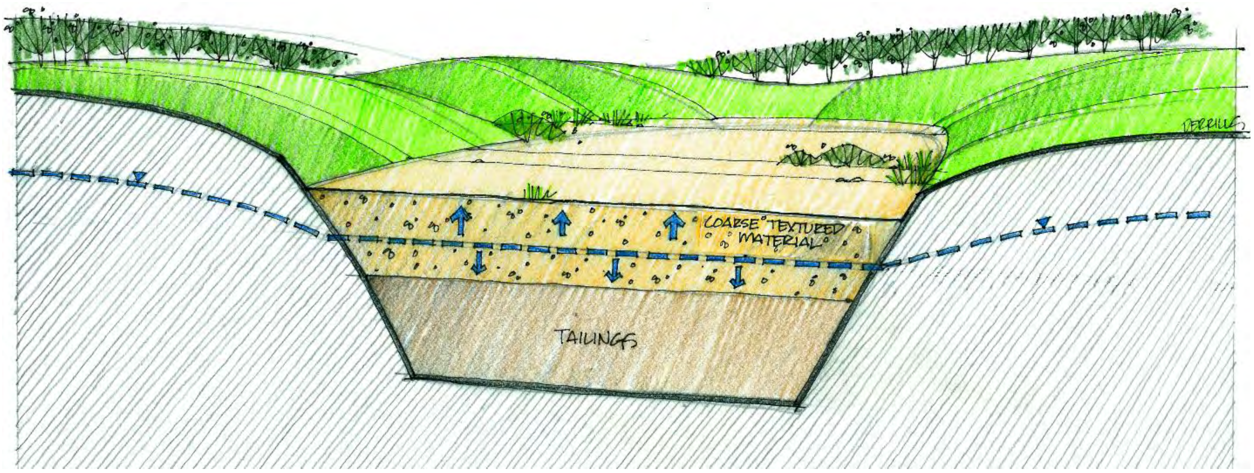

Figure 4-14. Saturated soil or rock cover system exploiting the position of local phreatic surface.

Use of a saturated cover must consider climate, topography, hydrology and hydrogeology, and the hydraulic properties of the waste and cover material. The *GARD Guide* discusses controlling the water table above the waste to limit ML/ARD (referred to as a Partial Water Cover in the *GARD Guide*).

4.5 Integration of Landforms and Cover Systems

Evaluating a single structure within a landscape is often referred to as landform design and is a fundamental consideration when designing cover systems for reactive material storage. Poor surface water management and landform instability are common causes of failure for cover systems globally (MEND, 2004). Many failure modes result from a design methodology that attempts to build engineered structures to oppose natural processes rather than integrating engineering systems based on natural analogues with the surrounding setting (Ayres et al., 2006).

Landform design depends on climate, geology, soils, local hydrogeological setting, topography, constructability, and final land use. Long-term sustainability is a challenge for landform design due to timeframes that may be on the order of hundreds of years. Changes during this period are difficult to predict and quantify yet will affect the system. Physical, chemical, and biological processes all affect the evolution of a system, and each process will affect the landform uniquely over time. A description of one design methodology for developing a sustainable final landform is available in MEND (2007).

The final landform design, which includes the cover system, depends greatly on the mine closure objectives set out in a mine's closure plan. Generally, the reclaimed landscape must be returned to a productive land use. Examples include wildlife habitat, traditional uses by aboriginal communities, community recreation, and commercial forestry. Successful reclamation will not restore a landscape but rather provide conditions for a landscape to develop toward an equivalent pre-mine capability, or a capability that meets the agreed upon land use.

The most central priority of landform design is to create a stable landform. Geotechnical stability is perhaps the most central for all mine closure regulations. This is achieved by having the landform meet slope, shape, and surface water management criteria. It should be noted, however, that the phrase "stable landform" in the context of physical stability is one that is commonly used as part of mine closure planning but is rarely defined. The issue is that the word "stable" is subjective, which can result in misconceptions and misunderstandings regarding performance. The term stable can be misused interchangeably with static. The phrase "stable landform" must be defined from a geotechnical engineering perspective; in terms of geotechnical stability of the landform, and/or near surface, or veneer, stability of the cover system.

4.5.1 Geomorphic Approach to Landform Design

Defining stability over long timeframes can be difficult without stability criteria outlined from landform objectives. Over long periods, landforms will evolve geomorphologically and erode, as will surrounding non-mine landscapes.

The geomorphic approach discussed in this guidance does not imply, for example, reducing and creating concave slopes that blend with the surrounding "natural environment". That is not to say all landforms following geomorphic principles are considered "stable". Sand dunes are one such example of a "natural" landform that are unstable and under constant instability. Likewise, an uncovered waste rock dump comprised of large boulders at the angle of repose is an engineered analogue to natural mountain block field. The point being, both stable and unstable landforms exist naturally and in the engineering realms. Therefore, a geomorphic approach is one that recognizes that the engineered landform and cover system, like the surrounding landscape, will evolve due to the driving forces in the geomorphic system; namely, climate and gravity.

Climate, as a 1st order controlling factor, influences:

i) Rainfall/solar insolation of area;
ii) Vegetative growth;
iii) Style of weathering/erosion process; and
iv) Hydrologic processes (e.g., fluvial, glacial).

To expect no evolution to occur highlights a failure in understanding geomorphic principals. Settlement, minor slumping, erosion, and other various slope processes are inevitable and should be considered within the context of a robust design. This is typically undertaken through numerical modelling, with the results measured against static and dynamic factor of safety design criteria.

From a geomorphic perspective, and arguably also a geotechnical one, landforms will often be at their most vulnerable to instabilities during the early stages of construction and during placement of the cover system. For sloping waste surfaces, two options exist for placement of the cover system, either construction from the bottom-up, or from the top-down. Each construction technique comes with advantages and risks.

When placing the cover from the top-down on a slope, there is the risk for bottom slopes to be less protected against runoff as water may be shed from the cover system upslope. Top-down cover construction followed by initial establishment of vegetation for erosion control has significant potential to result in late and inadequate vegetation for freshet or monsoon periods of the next year. There are also advantages for constructability on higher angle slopes, where equipment may be limited, having to work against gravity.

With bottom-up construction, there is a risk of material from upper slopes to become dislodged or wash down the slope as lower cover material is being placed. An advantage to bottom-up cover placement is when landforms take years to construct. Sometimes lower slopes are available for reclamation years earlier while construction continues the top; this is especially true for dykes. Construction from the bottom-up provides the lowest areas of the cover system the longest growing opportunity for initial vegetation in the year of construction activity. This is especially important as the lower portions of the slopes possess the greatest catchment and therefore greatest erosion risk.

There is also merit in applying progressive reclamation to larger storage facilities with construction spanning several years from one end to another. Placing the cover system from the top and bottom along the length of the facility as waste material is being deposited may be applicable for some landforms. In this way, the opportunity to learn as the facility is being reclaimed is possible, and this adaptive learning applied to future cover system placement.

In addition, some operational constraints may prohibit the use of top-down construction. In these circumstances, specifications pertaining to the percentage of non-vegetated surface area that can exist on the landform at any time before construction continues can be helpful. The design can also be modified to incorporate features that limit concentrated downslope runoff, thus decreasing erosion and instability potential. The higher upfront construction costs of bottom-up construction may be offset by lower maintenance and repair expenses, as well as the timeframe to meet stakeholder expectations.

Landforms and cover systems should be thought of as an integrated design (Figure 4-15). Failure within either the cover system or the landform will ultimately increase the risk of failure of the other. Early geochemical and geotechnical characterization of materials provides a strong basis for a chosen landform and cover system design. This minimizes final closure work, maximizes the quality of the outcome, and reduces the risk of failure with costly associated remediation.

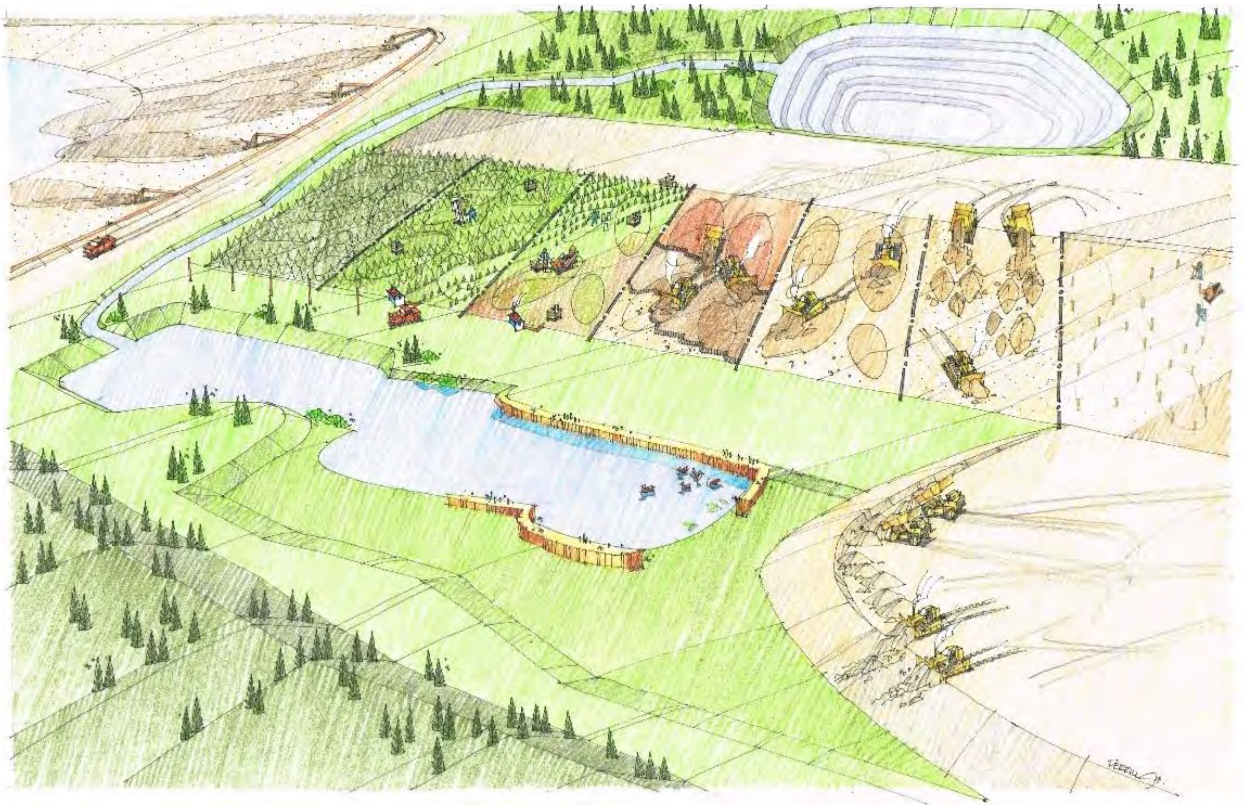

Figure 4-15. Cover systems as part of landscape and landform integration.

4.5.2 Cover Systems as Part of Watershed Management

Previous cover system guidance documents focus on managing water at a landform scale. This document advocates collective water management across multiple landforms to the landscape/watershed scale (Figure 4-16). The hydrologic landscape framework for integrating multiple discrete hydrological landform units across a landscape was developed by Devito et al. (2012). Under this framework, individual hydrologic units (HUs) have characteristic soil properties that result in distinct soil-vegetation-atmosphere interactions. HUs emphasize differences in hydrological responses of the hydrological response areas (HRAs) to climate cycles.

An HRA is an area of any landscape exhibiting similar soil texture and hydraulic conditions, and therefore producing similar hydrological regimes, which yield a characteristic water storage, scale, and type of flow processes. Once HUs have been identified and parameterized, they can be combined to characterize the response in conjunction with the landscape (HRA), while also understanding connection from one HU to another.

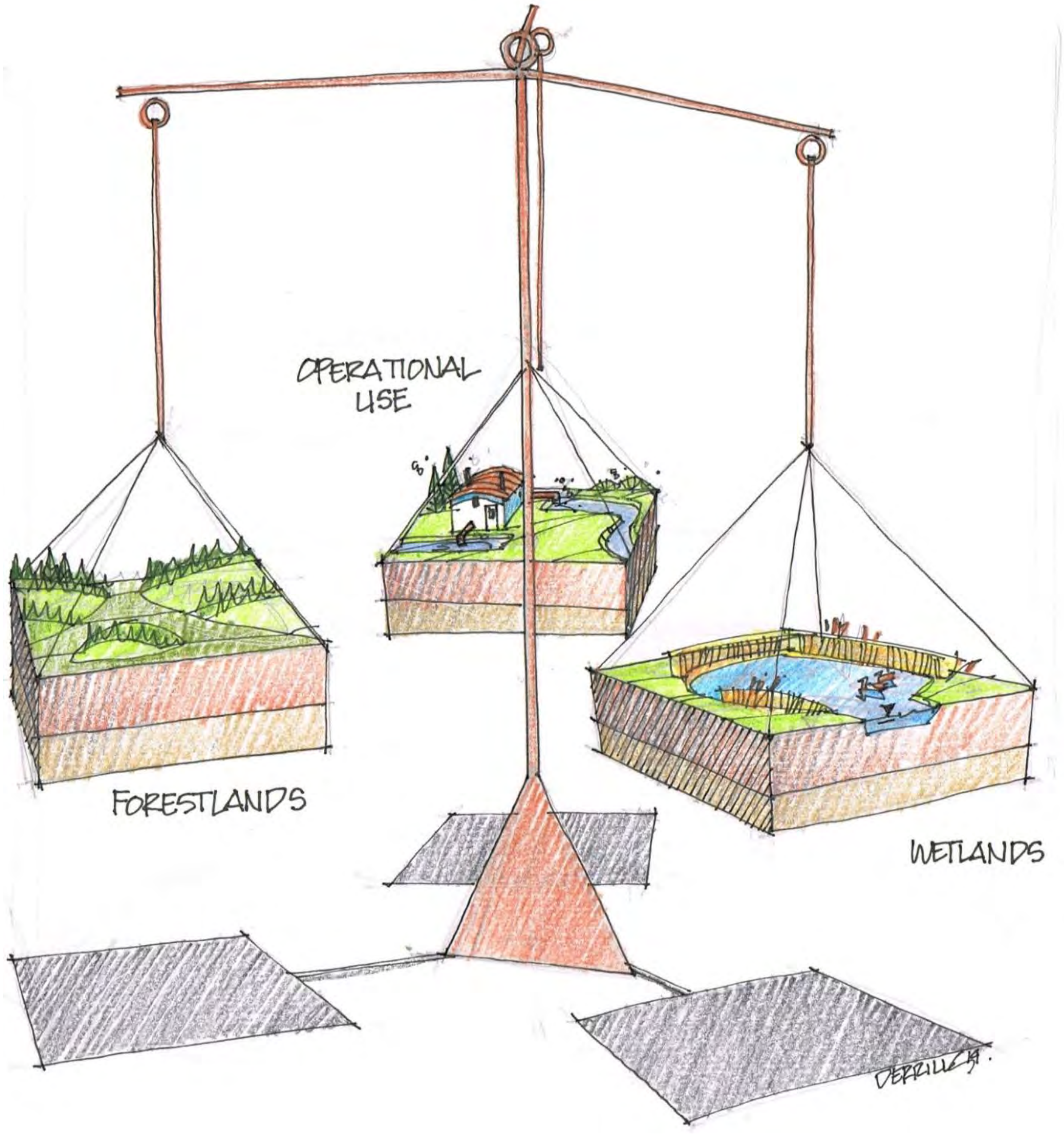

Figure 4-16. Balance of water resources on site for operations and closure activities.

The hydrologic landscape framework is a practical tool for determining hydrology of an area with varying landform configurations. The arrangement, distribution, and subsequent connectivity of the HUs and HRAs influence the water resources distributed across a landscape, its response to climate, the hydrologic connectivity, and, hence, functionality. Delineating HUs and HRAs in reclamation landscapes helps designers and managers handle substrate, landform, and landscape scale water resources. Appropriate delineation is also required to correctly identify the sinks and sources of water and constituents of interest in the watershed encompassing the mining activity.

In understanding the influence of climate on controlling NP, a distinction should be made between redirecting water from the potential chemical loads and keeping the cover system as dry as possible. Water resources may be required to support vegetation as part of reclamation strategies, to sustain the integrity of compacted clay layer (CCL) barriers, to be partitioned for ET to reduce runoff, and/or to enhance runoff to wetlands.

4.5.3 Control of Treatment Cost Using Cover Systems

Water management systems should be considered during mine development, mine production, and mine closure. Sound engineering can allow rational decisions regarding the level of investment in each stage. The earlier in the LOF closure of a waste storage facility is considered, the more options will be available. Cover systems are only one technological component of an overall closure plan. Some view water treatment as a competing technology to cover systems, but ideally these two mitigation strategies can work in consort to provide a more robust and effective system.

When designed and implemented correctly, cover systems can achieve several operational, reclamation and closure goals. As discussed in Section 4.3, some geochemical models assume that rates of chemical loading are independent of flow, which is often an overly conservative assumption. Well-designed cover systems can reduce NP and/or oxygen ingress, which reduces the volume of water to be treated or the quantity of stored acidity processed, respectively. By reducing the magnitude of NP and oxygen ingress, cover systems therefore provide a degree of reduction in the chemical load and, in some instances, sludge volumes to be managed (Figure 4-17).

For storage facilities with stored acidity products, cover systems also buffer large hydrological events, avoiding high concentration plug flow. In this same way, clean water can be kept clean. By better segregating meteoric water from mine waste contact water, mines can further reduce requirements for water management infrastructure and/or controls, such as storage reservoirs for untreated contact water. Cover systems can be used as part of some systems to replace active water treatment, allowing for passive water treatment options to be considered. Where water treatment is still required, cover systems can reduce the demands and costs. Cover systems are often needed for other reclamation land use goals, and so can minimize risks associated with a single water treatment plan. Although cover systems can be employed to manage the water requiring treatment, the impact a cover system will have on the entire watershed and those in the downstream receiving environment needs to be understood.

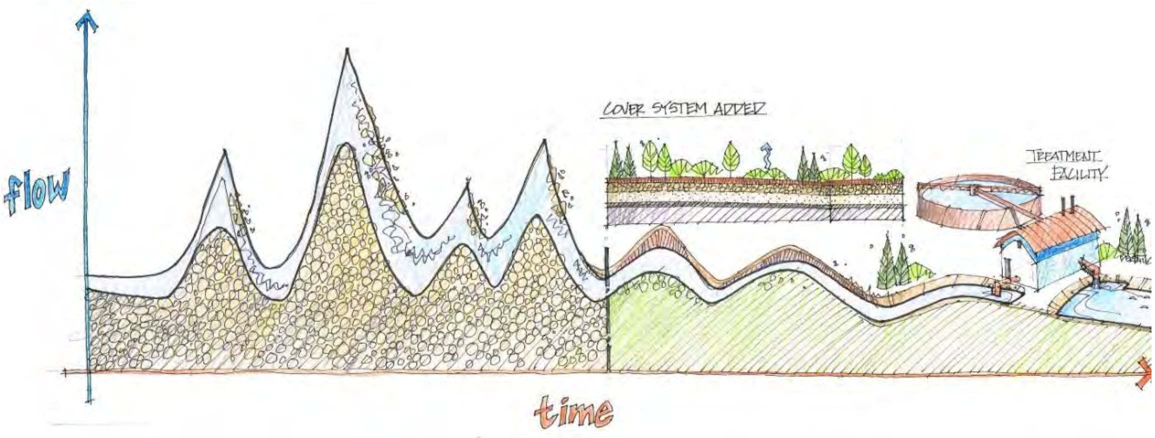

Figure 4-17. Addition of cover system and the potential effect on hydrograph response for water treatment.

4.5.4 Cover System Impact on Off-Lease Water Resources

Cover systems can evolve along with vegetative succession, as can water quality and quantity. For this reason, it is important to consider cover systems in site water-balances and subsequent monitoring programs. For example, differences may arise between uncovered conditions during operations and those when the mine waste landforms are covered and reclaimed with the latter producing much less runoff from the site as whole. If downstream and offsite infrastructure is put into place (e.g., at river crossings) during operations, a change in hydrographic response at closure can adversely affect infrastructure (Figure 4-18).

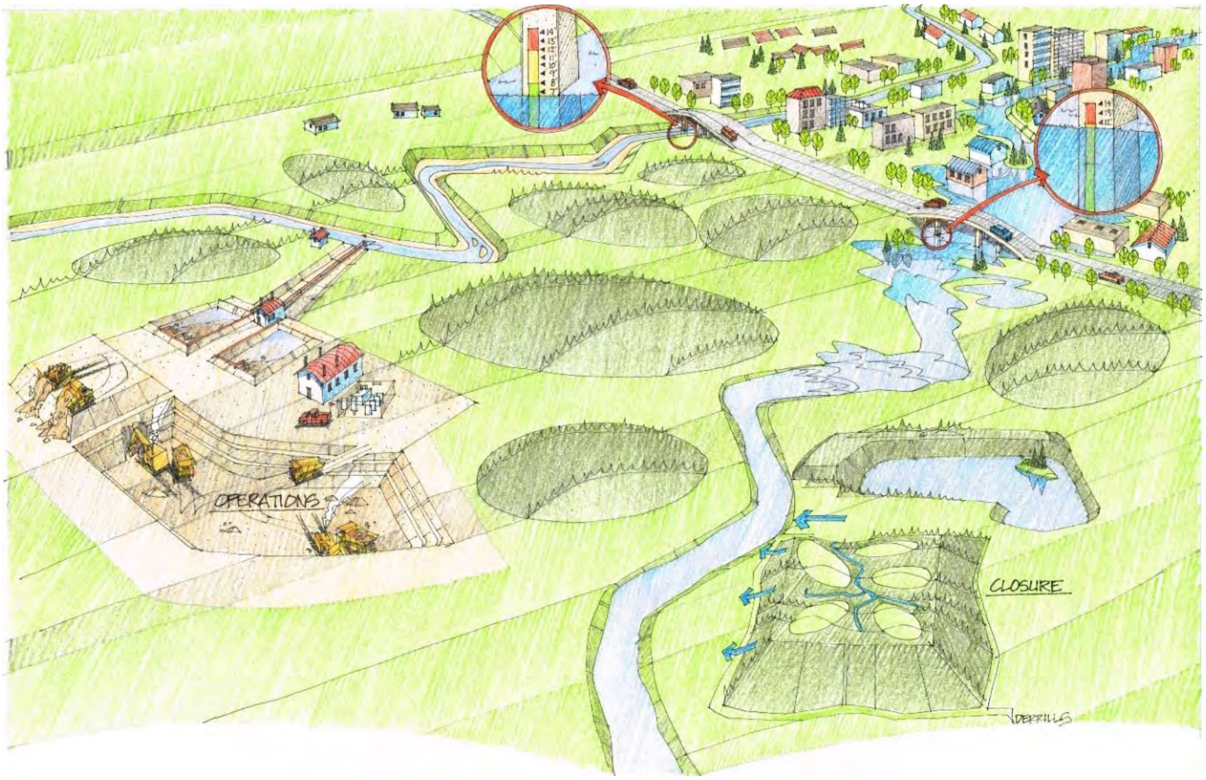

Figure 4-18. Offsite discharge to river and downstream infrastructure during operations vs. closure.

5 IMPORTANCE OF CLIMATE SEASONALITY

5.1 Climate

The *GARD Guide* demonstrates the importance of climate for the selection of cover system design alternatives required for different dominant climate mechanisms (Figure 5-1). Climate is also used in this document to explain how performance will be affected for not only NP, but also oxygen ingress, erosion potential, and potential constructability issues. Furthermore, this document highlights how climate understanding can be improved using seasonal tendencies to inform cover system designs beyond an annual basis.

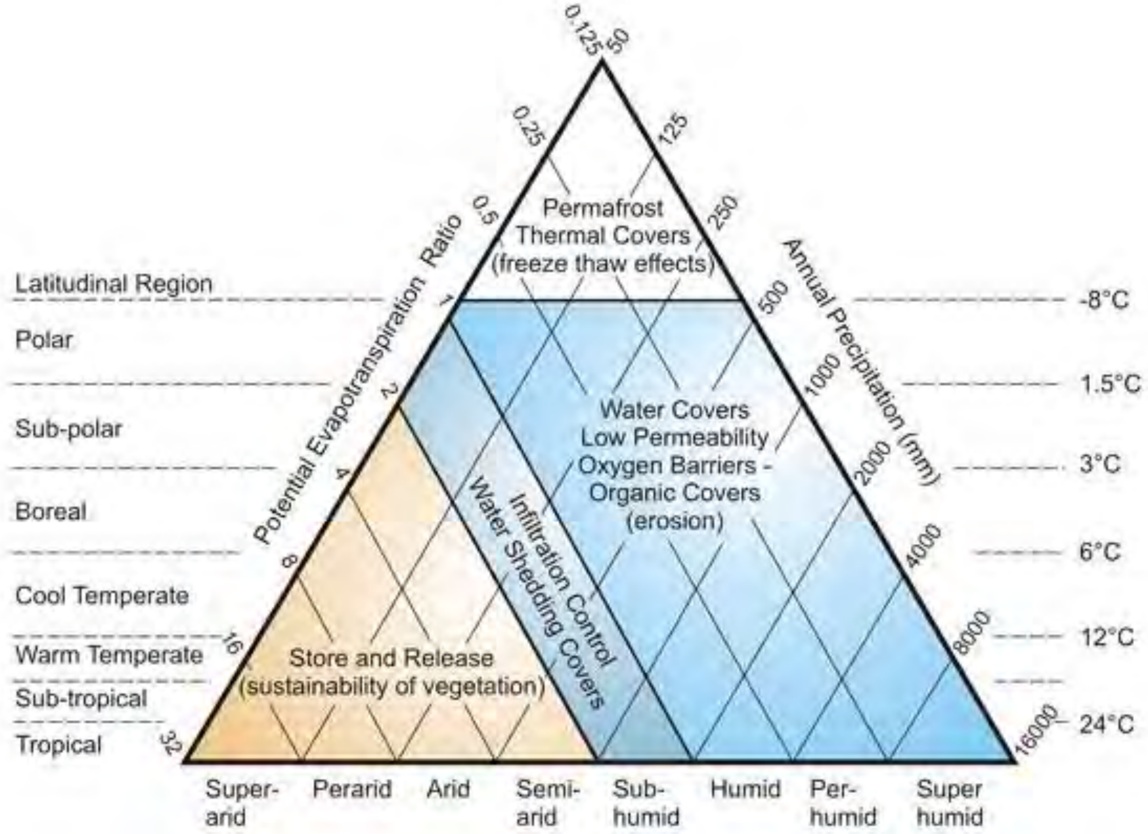

Figure 5-1. Cover systems and climate types (*GARD GUIDE*, 2011).

Figure 5-1 illustrates how an optimal cover system might vary with climate classification. It provides a broad understanding of how climate will affect cover system design. To gain a more detailed view of the influence of climate on cover system design, further progression from annual to a seasonal timescale is necessary. What is required is an understanding of climate's effects on cover system design within a framework that is transferable to other regions in hopes that cover systems are designed on a site- and climate-specific basis.

5.2 Seasonality

This document uses the Köppen-Geiger system (Peel et. al., 2007) to broadly differentiate climates around the world, largely because of its ability to reflect seasonal differences. Regional boundaries are determined by a large global dataset of long-term monthly precipitation and temperature records. Köppen-Geiger's strong ties to landscape signals such as vegetation and related soil development makes it useful for this document's chosen framework, which includes filters for climate, materials and vegetation. The major climate regions are tropical, arid, temperate, cold, and polar. Each region can be further divided into sub-regions.

The Köppen-Geiger system allows seasonality to be considered across all climate types. Arid regions, for example, may have annual PE values much greater than annual PPT, making a store-and-release cover system seem like a logical decision on an annual basis; but a short rainy season can be hidden by annual averages. During these periods, rainfall may be higher than evaporation potential, leading to higher NP than anticipated using annual averages. Seasonally high PPT will also require specific designs to manage runoff and erosion in addition to NP control.

Although mining activity is not widespread in all climates, major concentrations of mining are found in each climate type. For instance, temperate regions coincide with much of the eastern coast of Australia, New Zealand, Zambia extending into South Africa, and Peru extending into Chile. Similarly, arid regions capture the prolific mining regions in northwestern Australia and northern Africa, as well as southern portions of Peru. Mining in tropical climates occurs in far fewer regions but includes northern Brazil and Indonesia (Figure 5-2).

The framework presented applies to all climate types to help identify dominant site-specific attributes relevant to cover system design. To address the dynamic nature of intra-annual climate variability (seasonality), the tropical, arid, and temperate regions can be divided into 30 sub-regions based on seasonality of temperature and precipitation.

Table 6-2 (in Section 6) allows a designer to identify influential climate components involving energy and/or water balance. Key opportunities can be exploited and attributes that merit caution identified. Areas of interest can be when, or if, a surplus or deficit of water will occur on site and in what quantity. When water can be released off-site will largely depend on climate.

Detailed site-by-site characterization will still be required, but the Köppen-Geiger climate classification system improves a designer's ability to work at a conceptual level. The increased information contained in the classification system also allows designers to conceptualize cover system functions across the site. For example, if a system is required at other portions of the site at higher elevation (or for a different slope aspect), a designer can determine whether the variation calls for an alternative design by modifying the seasonal temperature profile or precipitation regime.

Furthermore, because Köppen-Geiger is broken into seasonal temperature and precipitation trends, the possible effects of climate change can be applied to a site. This allows for conceptual cover system designs to evolve from the environmental assessment stage early in the LOM to the final closure designs that may occur 50 years later.

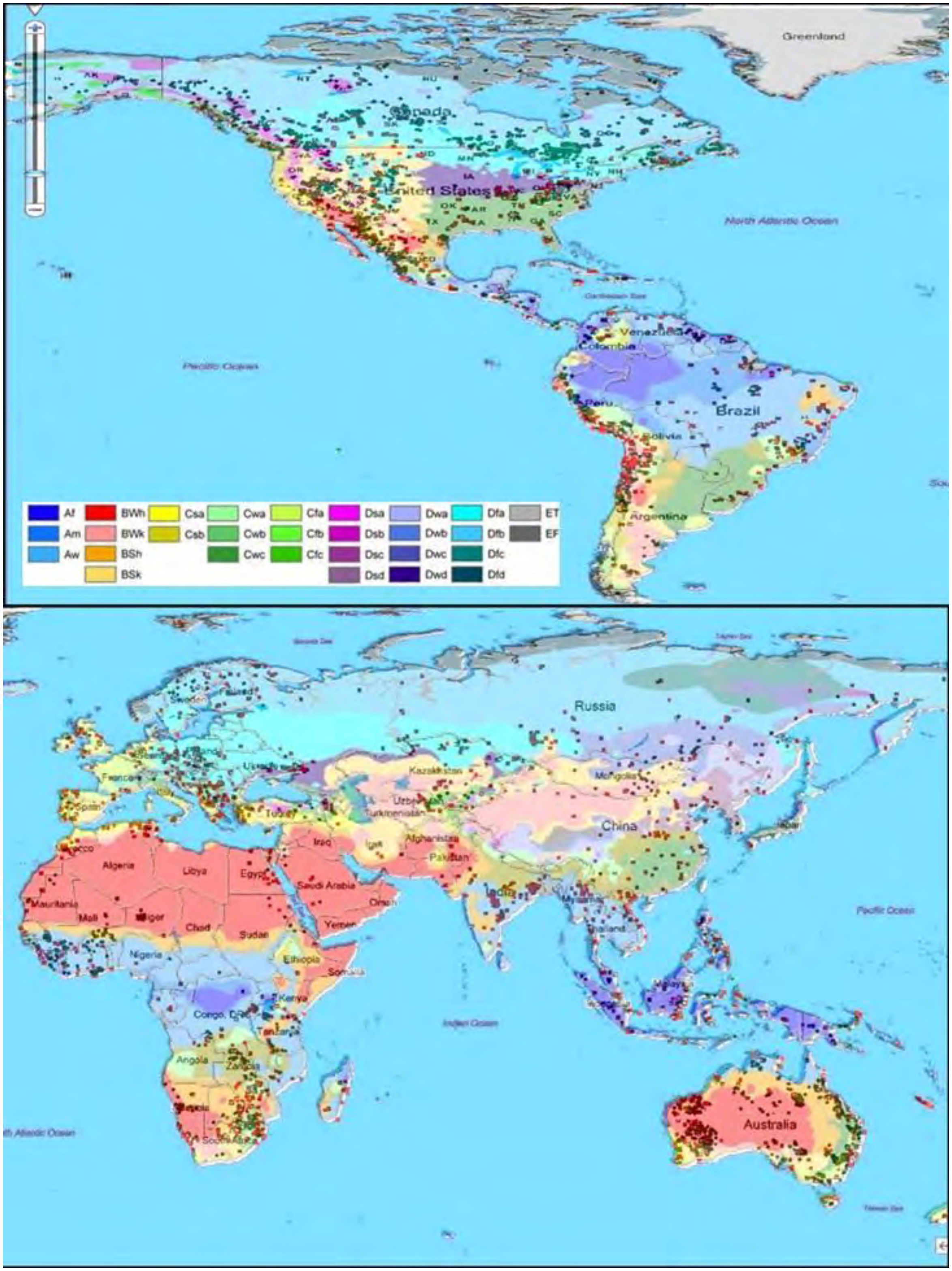

Figure 5-2. Climate classification regions overlain on mines in various stage of development for the Eastern and Western hemispheres.

6 COVER SYSTEM DESIGN TOOL

6.1 Introduction to the Cover System Design Tool

The information provided within this tool is not a replacement for the site-specific classification and engineering required for cover system design. The tool is a means of beginning early conceptualization to help focus further investigation at a site level and to begin to form realistic expectations for cover system performance.

This document considers cover system design in a hierarchy framework. Each step of the hierarchy represents an attribute of the site (climate, geology/materials, or topography) that provides opportunity for, or can constrain, design alternatives to achieve the desired performance. For example, when the first step – climate – is applied, some generic cover system designs will not be capable of meeting performance criteria. Each attribute highlights critical issues or processes that can be utilized, or must be mitigated, to achieve the selected performance criteria of the conceptual design. Figure 6-1 schematically describes the cover system design framework.

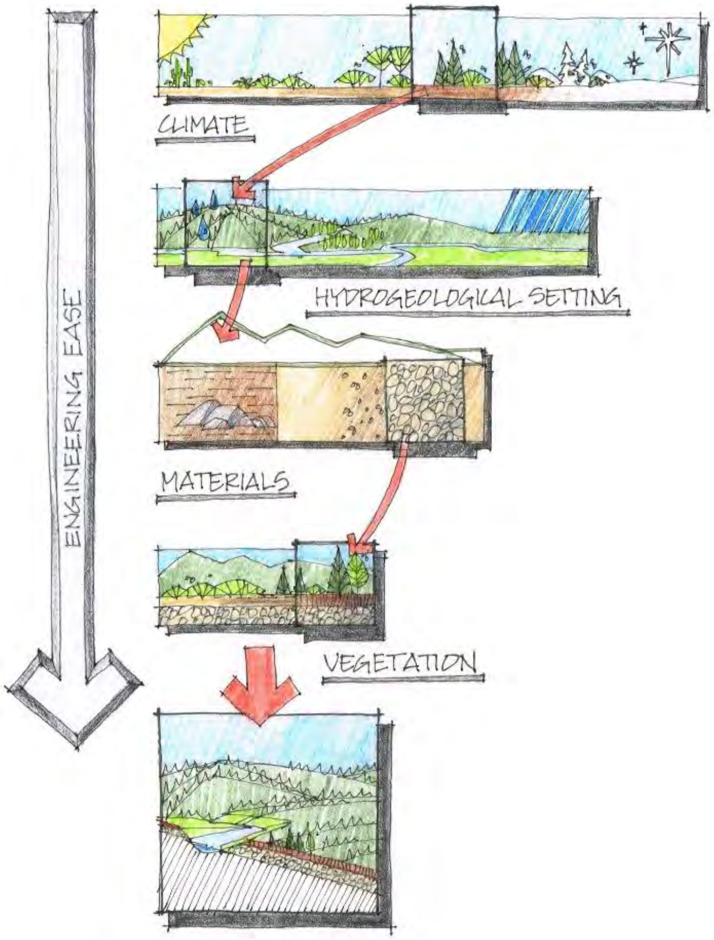

Figure 6-1. Conceptual cover system design framework portraying four filters for climate, hydrogeology, materials, and vegetation.

This document focusses on cover system design for storage facilities that contain reactive materials that require oxygen or meteoric water isolation. The *GARD Guide* explains how practitioners can characterize and classify wastes in this way. It is therefore recommended users begin by characterizing the geochemical issues facing them by first referring to the *GARD Guide*, and then transition to this document based on the various recommended technologies (Figure 6-2).

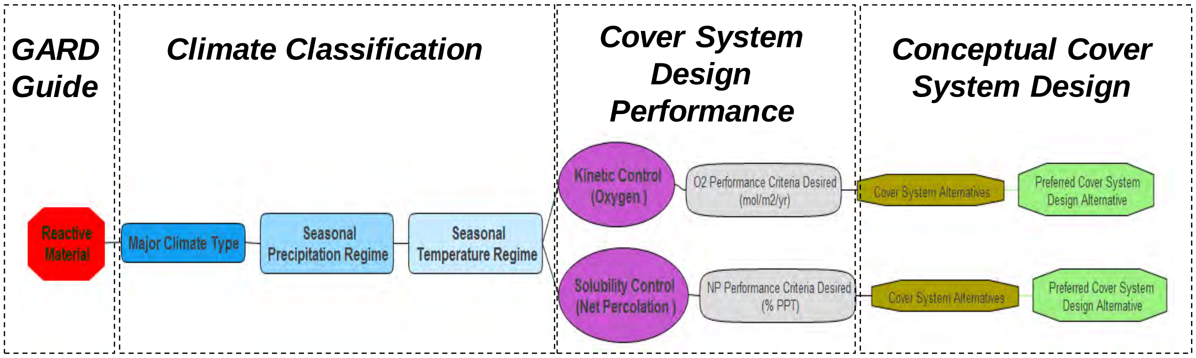

Figure 6-2. Global cover system design tool workflow.

6.2 Climate Classification

This document advocates the use of modified Köppen system (Peel et al. 2007) to broadly differentiate between climate types globally, largely due to its classification scheme incorporating seasonality. Regions of the world are divided based on a large global data set of long-term monthly PPT and temperature station time series. These climatic thresholds were developed in part due to field observations using landscapes signals, such as vegetation. Due to its strong ties to landscape signals, such as vegetation and related soil development, the Köppen system is attractive for the framework put forth in this guidance document, which includes filters for climate, materials and vegetation. Based on the classification system, five major climate types exist:

- **Tropical** (A)climates;
- **Arid** (B) climates;
- **Temperate** (C) climates;
- **Cold** (D) climates; and
- **Polar** (E) climates.

Cold and Polar regions can be grouped together from a cover system design perspective and both climates have been covered in more detail as part of the *MEND Cold Regions Guidance Document* (MEND, 2012). However, the framework presented here is applicable to all climate types to help identify dominant site-specific attributes beneficial to cover system design.

For a more visual approach to determine mine site climate classifications, numerous interactive online mapping tools exist (Table 6-1).

To address the dynamic nature of intra-annual climate variability (seasonality), subtypes exist for both PPT and temperature (Temp) (Table 6-2), which further sub-divide tropical, arid, and temperate regions. These are denoted by lowercase letters for both subdivisions denoted in Table 6-2.

Table 6-1. External references for determining site Köppen-Geiger climate classification.

Region Specific	**Data Type**	**Climate Change Scenarios Available**	**Address**
Global	GIS Google Earth	Yes	http://koeppen-geiger.vu-wien.ac.at/shifts.htm
USA	Web based	No	http://www.plantmaps.com/koppen-climate-classification-map-united-states.php
Global	Google Earth	No	http://webmap.ornl.gov/sdat/kmz/ornldaac_ds10012.kmz

After site-specific seasonal climate has been classified, users are required to determine the geochemical control most applicable to their site-specific materials in their current and potential future states. Section 4.3 provides additional information to guide users in understanding whether the control of NP or oxygen ingress is most applicable, or both are required. These are referred to as:

1. Kinetic – Oxygen control
2. Solubility – Net percolation control

Once the geochemical control mechanism has been identified, qualitative performance criteria for both NP and O_2 have been developed based on site-specific climate (Appendix A). At the conceptual level, most designers may be looking to investigate designs that will lead to very low rates of O_2 and/or NP for their sites. However, further investigation with the tool may identify prohibitive elements of the design that influence designers into low, moderate, or high NP and/or O_2 rates.

Table 6-2. Köppen-Geiger climate classification system quantitative thresholds.

Major Climate	**PPT**	**Temp**	**Sub Region Description**	**Threshold***
A			**Tropical**	$T_{cold} \geq 18$
	f		• Rainforest	$P_{dry} \geq 60$
	m		• Monsoon	Not (Af) & $P_{dry} \geq 100\text{-}MAP/25$
	w		• Savannah	Not (Af) & $P_{dry} < 100\text{-}MAP/25$
B			**Arid**	$MAP<10\times P_{threshold}$
	W		• Desert	$MAP < 5\times P_{threshold}$
	S		• Steppe	$MAP \geq 5\times P_{threshold}$
		h	- Hot	$MAT \geq 18$
		k	- Cold	$MAT < 18$
C			**Temperate**	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		• Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		• Dry Winter	$P_{wdry} < P_{swet}/10$
	f		• Without dry season	Not (Cs) or (Cw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon}10 \geq 4$
		c	- Cold Summer	Not (a or b) & $1 \leq T_{mon}10 < 4$
D			**Cold**	$T_{hot} >10$ & $T_{cold} \leq 0$
	s		• Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		• Dry Winter	$P_{wdry} < P_{swet}/10$
	f		• Without dry season	Not (Ds) or (Dw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon}10 \geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very Cold Winter	(a or b) & $T_{cold} < -38$
E			**Polar**	$T_{hot} < 10$
	T		Tundra	$T_{hot} > 0$
	F		Frost	$T_{hot} \leq 0$

PPT: Precipitation sub-region classification; Temp: Temperature sub region classification.
*Table adapted and criteria described in Peel et al. (2007).

- MAP = mean annual precipitation,
- MAT = mean annual temperature,
- T_{hot} = temperature of the hottest month,
- T_{cold} = temperature of the coldest month,
- T_{mon10} = number of months where the temperature is above 10,
- P_{dry} = precipitation of the driest month,
- P_{sdry} = precipitation of the driest month in summer,
- P_{wdry} = precipitation of the driest month in winter,
- P_{swet} = precipitation of the wettest month in summer,
- P_{wwet} = precipitation of the wettest month in winter,
- $P_{threshold}$ = varies according to the following rules:
    - if 70% of MAP occurs in winter then $P_{threshold}$ = 2 x MAT,
    - if 70% of MAP occurs in summer then $P_{threshold}$ = 2 x MAT + 28,
    - otherwise $P_{threshold}$ = 2 x MAT + 14.
- Summer (winter) is defined as the warmer (cooler) six-month period of ONDJFM and AMJJAS

6.3 Conceptual Cover System Design

Cover system design alternatives are presented in the tool for all the performance criteria (i.e., from very low to very high) for both NP and O_2 management; cover system design alternatives are not presented for erosion control as provision of this aspect is not within the scope of the tool. Commentary is provided on cover system design alternatives discussed in the document presented for the very low performance criteria.

Throughout the conceptual framework, a colour classification scheme is used as follows:

- Green – good;
- Yellow – moderate; and
- Red - poor

The preferred cover system design appears at the top of the list in green. Where applicable, an alternative cover system design is presented below the preferred design; coloured yellow. The remaining cover system types are not recommended, in terms of meeting the very low performance range, and therefore coloured red.

For the preferred cover system design, four categories are colour coded as above that pertain to the design:

1. Overarching applicability;
    a. General commentary
    b. Specific commentary
        i. Design considerations
        ii. Construction considerations
        iii. Performance considerations
        iv. Climate considerations
2. Confidence in meeting performance expectation;
3. Indicative cost; and
4. Analysis and modelling complexity.

The cover system tool is displayed as print copies in Appendix A, however for a more efficient user experience, the tool ConceptDraw's MINDMAP software (http://www.conceptdraw.com/) is available for users.

7 APPLICATION OF COVER SYSTEM DESIGN TOOL

7.1 Introduction

The generic case studies outlined in this section are built around a hypothetical, average-scale mine waste rock storage facility (WRSF) with reactive mine materials found globally. Three climate scenarios, or conditions, were used to evaluate the case studies: a temperate (humid continental), tropical, and arid climate. The methodology is based on information and the evaluation framework in this guidance document.

Modelling was conducted in two phases. The first involved 1-D soil-plant-atmosphere models of each cover system using VADOSE/W (Geo-Slope International, 2008), and climate and geotechnical material properties as inputs. A unit area column 100 m deep was chosen to determine annual NP rates and oxygen flux for 100 years of climate data.

Second, the results of the 1-D vadose modelling and the waste rock geochemical characteristics were applied to an analytic model to predict average annual acidity loading rates for the case studies. For the first scenario, the cover system design methodology presented in this document is summarized to provide a greater understanding of the conceptual application of the methodology. To avoid redundancy, this methodology was not provided for the remaining scenarios.

The following specifics are in the attached appendices:

- Waste rock geochemistry characteristics;
- Climate databases;
- Physical setting;
- Description of the numerical model;
- Vegetation dynamics; and
- Model assumptions and limitations.

7.2 Scenario Matrix Summary

Multiple-scenario sensitivity analysis is used to illustrate how contrasting climates, geochemistry, and cover system materials influence geochemical loading. The scenarios follow the matrix shown in Table 7-1. The focus is on changing climate conditions, material characteristics, and geochemical properties of the reactive material. The base case walks through the methodology and framework in this document.

Table 7-1. Scenario matrix for comparing waste rock management approaches and cover system performance for a generic case study.

Parameter	Scenario 1a (Base)	Scenario 1b	Scenario 2a	Scenario 2b	Scenario 3a	Scenario 3b
Climate	Humid continental (Dfa)	Humid continental (Dfa)	Arid (BWh)	Arid (BWh)	Tropical (Af)	Tropical (Af)
Waste Material	Coarser-textured ROM well-graded waste rock	Coarser-textured ROM well-graded waste rock	Coarser-textured ROM well-graded waste rock	Coarser-textured ROM well-graded waste rock	Finer-textured ROM well-graded waste rock	Finer-textured ROM well-graded waste rock
Cover Configuration	1 m growth medium/store-and-release layer 0.5 m compacted till barrier layer	2 m growth medium/store-and-release layer 0.5 m compacted till barrier layer	1 m growth medium/store-and-release layer	2 m growth medium/store-and-release layer	2 m growth medium/store-and-release layer 0.5 m CCL $1x10^{-7}$ cm/sec	1 m growth medium/store-and-release layer 0.5 m CCL $1x10^{-6}$ cm/sec

Scenario 1 simulates two different cover system configurations (1a/b). The second permutation of the first scenario increased the growth medium thickness to 2 m and the rooting depth to 2 m. The leaf-area index (LAI) is used by VADOSE/W to reduce the amount of net radiation to the soil surface, which then reduces the computed actual evaporation. Simply, LAI controls how energy at the surface is partitioned between that available for direct evaporation from the soil and that available to the plants for transpiration. For the temperate humid continental scenario, LAI was set equal to one.

Scenario 2, an arid climate, simulates two different cover system configurations (2a/b). The second permutation increased the growth medium thickness to 2 m and the rooting depth to 2 m. Due to the high atmospheric demand for water throughout the year, a moisture store-and-release cover system was assumed. For the arid climate, LAI was set equal to 1.8.

Scenario 3, a tropical environment, also involves two different cover system configurations (3a/b). The first permutation employed a lower-permeability barrier layer with a saturated hydraulic conductivity of $1x10^{-7}$ cm/s. The second assumed the permeability of the barrier layer increases to $1x10^{-6}$ cm/s to better understand the sensitivity of barrier layer hydraulic conductivity on NP and management of oxygen ingress. For a tropical environment with high solar radiation and where plants were not moisture-limited, LAI can be high. LAI for this scenario was the highest of all three climates and set to 2.7, which is the maximum allowable within VADOSE/W, and results in all net radiation partitioned to energy for transpiration. Additionally, rooting depth extended to the maximum growth-medium depth.

7.3 Setting Design Objectives

The objectives for the scenarios presented in the case studies are like objectives that might be identified by those tasked with closure globally. Identifying that the geochemical issue is reactive mine waste and not inert waste is a first step. Recognition that hydrogeology of the site will be conducive to seepage reporting to nearby environmental receptors from the WRSF will be the next step in identifying and characterizing the geochemical issue. Therefore, the cover systems' primary objective is assumed to be: *Minimize the release of acidic seepage and metal and/or metalloid leaching to the environment from the WRSF.* Additional objectives, such as those involving land use, might also be included here, as well as erosional and geotechnical stability. However, for simplicity, the focus for these generic case studies is the cover system objective as stated (Table 7-2).

To meet this objective, two approaches can be used. First, controlling NP will prevent transport of soluble acidity, and dissolved oxygen to a lesser degree. Alternatively, a cover system design may aim to kinetically control further oxidation reactions of reactive material by limiting the ingress of oxygen.

Climate and geochemistry must be evaluated to determine which cover system function is more critical to achieving the overarching objective of limiting *release of acidic seepage and metal and/or metalloid leaching* to nearby receptors. The 20-year construction period of the WRSF allowed oxidation of the material to proceed without significant limitation on oxygen availability throughout the entire WRSF, although scaling factors were applied for the different climate regimes. This continued oxidation of material prior to cover placement is common, and accumulation of stored acidity results. Cover system objectives will likely need to target a reduction in the infiltration of the meteoric waters that have the potential to report as NP, thus flushing many of the stored acidity products. Alternatively, some balance between management of NP and management of seepage will need to be developed.

Table 7-2. Cover system design attributes for achieving desired objectives.

SCENARIO	Key Cover System Functionality	Exploited Attributes	Cover System Tool Selection	Commentary
Humid Continental (Dfa)	Reduce NP largely through evapotranspiration, but also through diversion (runoff)	• Large store-and-release during growing season by vegetation. • Store-and-release layer sufficient to contain spring melt. • Low-permeability layer to reduce NP from large melt years promoting runoff.	• For very low NP, Barrier - compacted layer required within cover system. (Appendix A1-3)	• CCL must have 10^{-7} cm/s or less. • Ensure adequate material volumes of compacted material and growth medium available with correct specifications. • Characteristics of overlying growth medium thickness is critical to long-term CCL performance.
Arid (BWh)	Reduce NP largely through evapotranspiration	• Large store-and-release during growing season by vegetation, but mostly evaporation.	• For very low NP, store-and-release cover system. (Appendix A4-16)	• For appropriate cover material and applying QA/QC to ensure homogeneity (no segregation of material during placement, for this climate there is less risk in achieving very low NP rates. • Due to aridity, there is little reliance on vegetation to provide erosion protection or enhanced reductions in NP due to higher AET rates. • Key design considerations are landform stability (erosion and sediment deposition) and preventing segregation of cover system material during placement. • Store-and-release layers with a coarser and finer textured segregation near/at surface allows preferential flow deeper in cover profile during high rainfall, which leads to higher NP rates.
Tropical (Af)	Reduce NP largely through diversion (runoff)	• Finer-textured residual soil to form low permeability compacted barriers promoting runoff. • Store-and-release during growing season by vegetation.	• For very low NP, geosynthetic layer required. (Appendix A2- 4)	• For high rainfall, and approximately unit gradient flow conditions, and no storage capacity due to consistent wet conditions, NP is a function of the CCL k_{sat}. • This can represent a significant flux considering annual precipitation can be upwards of 4 m. • Therefore, efficacy of geomembranes should be considered to achieve a very low NP rate with confidence.

7.4 Net Percolation Modelling Results

The distribution, magnitude and timing of precipitation events all serve to interact with the cover system configuration, which includes the hydraulic conductivity of materials as well as their available water storage capacity (AWSC). In turn, the interaction manifests as differences in NP across climates and due to differing hydrological regimes. Table 7-3 presents a NP performance summary for each climate and cover system configuration. Although a geosynthetic barrier layer is recommended by the tool for tropical climates, the case study demonstrates the effect of assuming a CCL would be sufficient. As is evident, NP in this climate is directly proportional to the hydraulic conductivity of the CCL.

Table 7-3. Net percolation summary for generic case study sites and quantitative cover system performance assessment based on model results for increasing store-and-release/growth medium (GM) thicknesses and changing saturated hydraulic conductivity. GM=growth-medium layer; VL=very low; M=medium; H=high.

		Humid Continental		**Arid**		**Tropical**	
		1 m GM	2 m GM	1 m GM	2 m GM	CCL (cm/s) 1×10^{-7}	CCL (cm/s) 1×10^{-6}
NP (%)	• Min	~4	<0.5	0	0	~5	~25
	• **Average**	**~7**	**<1**	**0**	**0**	**~10**	**~40**
	• Max	~10	~2	~40	~35	~30	~50
Surface AWSC (mm)		~160	~320	~40	~80	~90	~90
Lowest Permeability Layer (cm/s)		5×10^{-7}	5×10^{-7}	4×10^{-3}	4×10^{-3}	1×10^{-7}	1×10^{-6}
Qualitative NP Performance Range		VL-L	VL	VL- H	VL- H	VL-L	L-H
Probability of achieving "Low" Performance Criteria (%)		100	100	~65	~70	100	~10
Probability of achieving "Very Low" Performance Criteria (%)		~20	100	~60	~70	100	0

7.5 Oxygen Ingress Modelling Results

Managing gas transport across cover systems is challenging in arid and temperate climates. For the latter, achieving low oxygen ingress rates is certainly possible, but a layer with relatively robust moisture retention characteristics is typically required. For tropical climates, the modelling results highlight a potentially important mechanism pertinent to sulphide oxidation. Oxygen ingress not only occurs through advective and diffusive gas transport, but also as dissolved oxygen within NP. While the diffusive and advective flux of oxygen was restricted to less than 0.5 g/m^2/year using the 1×10^{-7} cm/s barrier (Table 7-4), the long-term loading of acidity in drainage continued long after stored acidity had been depleted as a result of dissolved oxygen within NP. If the long-term loading in seepage is unacceptable or fails to meet performance criteria, a further reduction in NP would be required.

Table 7-4. Oxygen ingress summary for generic case study sites and quantitative cover system performance assessment based on model results. GM=growth-medium layer; VL=very low; L=low; M=medium; H=high.

	Humid Continental		**Arid**		**Tropical**	
	1 m GM	2 m GM	1 m GM	2 m GM	CCL (cm/s) $1x10^{-7}$	CCL (cm/s) $1x10^{-6}$
Oxygen Ingress (g/m^2/yr)						
• Min	~85	~65	~1580	~630	<1	<2
• **Avg**	**~600**	**~270**	**~2450**	**~980**	**<1**	**<2**
• Max	~1020	~675	~4550	~1675	~3	~85
VL – L – M – H	H-VH	H-VH	VH	VH	VL	VL-H

7.6 Geochemical Loading Modelling Results

The differences in oxygen ingress and NP rates only differ among climates and not between paired scenarios for the 20 years when WRSFs remain uncovered prior to construction of the cover system. Total potential acidity for all scenarios was based on the amount of sulphides within the WRSF. The sulphur content for all scenarios was assumed to be 1 % by weight. Stored acidity represented the actual quantity of acidity produced due to sulphide oxidation, some of which remained in the WRSF, and some of which was removed over the model period due to transport resulting from net percolation. The percentage of maximum potential acidity converted to stored acidity is presented in Table 7-5.

Table 7-5. Geochemical load summary for generic case study sites and quantitative cover system performance assessment based on model results. GM=growth-medium layer.

	Humid continental		**Arid**		**Tropical**	
	1 m GM	2 m GM	1 m GM	2 m GM	CCL (cm/s) 1x10^{-7}	CCL (cm/s) 1x10^{-6}
Stored acidity prior to cover (tonnes)	~1.15 x 10^6	~1.15 x 10^6	**~2.30 x 10^6**	**~2.30 x 10^6**	~0.11 x 10^6	~0.11 x 10^6
Stored acidity @ 100 years (tonnes)	~1.15 x 10^6	~1.30 x 10^6	**~3.90 x 10^6**	~2.95 x 10^6	~0.12 x 10^6	~0.13 x 10^6
Potential acidity converted to stored acidity (%)	~10	~9	**~25**	~19	~1	~1
Total acidity discharged from WRSF (tonnes)	~17,500	~10,600	~4,050	~1,075	~110,000	**~130,000**
Geochemical Control	Solubility	Solubility	Solubility	Solubility	Solubility (Kinetic @ ~100 years)	Solubility (Kinetic @ ~45 years)

When stored acidity present in the WRSF fell below zero in the model, the change suggested NP-derived drainage had flushed out all stored acidity. In such instances, the system became kinetically controlled by the oxygen flux and the acidity load in drainage was equivalent to the acidity derived from the oxygen flux, both dissolved and diffused. If the acidity load in WRSF drainage was less than stored acidity generation rate, there was reduced utility in controlling oxygen ingress. One could argue that when oxygen flux is low, a higher NP rate for the cover system would flush out the stored acidity; however, this assumes that flushing is uniform throughout the facility; a situation that can be challenging to achieve and/or even demonstrate. In addition, dissolved oxygen transported by NP must be accounted for. If the intrinsic oxidation rate is greater than the acidity load determined by oxygen flux, then formation of acidity load is limited kinetically by oxygen flux.

The generic case studies clearly illustrate that different sites around the world will require site-specific cover system designs, based on climate, hydrogeologic setting, available cover system materials and characteristics, and waste material characteristics.

7.7 Implications of Cover System Design

The generic case studies were developed to highlight the influence that climate will have on cover system design. Nevertheless, the studies do illustrate that the “first filter” cover system designers should examine is site-specific climate conditions. This lens, combined with an understanding of the geochemical characteristics of the waste material, site-specific characteristics (and volumes) of cover material, and the physical setting of the waste storage facility, allows designers to develop a first-pass conceptual model of what is realistically possible for a given site's conditions. This first-pass conceptual model is invaluable because it allows for a focus on cover system designs that can meet site and waste storage facility closure objectives, and design criteria early in the closure planning process. In addition, it draws attention to the next steps in the design process — the need for analytical and numerical modelling, as well as development of information to complete a table such as that illustrated in Table 7-6, which is repeated here for clarity.

Table 7-6. Example of conceptual cover system design expectations (for net percolation).

NP Range	Design?	NP (%)	Cost $/ha	Water Treatment Reduction	Water Quality Target	Comments
Very Low	Plateau	??%	$??	% ??	?	• Use at other locations? • Meets closure objectives? • Applicability to your site? • Closure planning support studies required?
	Slope	??%	$??	% ??	?	
Low	Plateau	??%	$??	% ??	?	
	Slope	??%	$??	% ??	?	
Moderate	Plateau	??%	$??	% ??	?	
	Slope	??%	$??	% ??	?	
High	Plateau	??%	$??	% ??	?	
	Slope	??%	$??	% ??	?	

? : represents site-specific values to be determined during early conceptualization.

This table can be completed at all stages of a project, from conceptual to detailed, and the failure mode effects analysis conducted at each stage can focus on required support studies and/or mitigation to the cover system designs deemed necessary to reduce risks to acceptable levels. Although represented above with question marks, in practice the table can be filled in on a site- or project-specific basis. Many of the values will come from cover system design objectives and criteria, but other will come from operations. More comprehensive analyses, such as that presented for the generic case studies, are required to take a project from the conceptual design stage to the next stage of a project.

8 COVER SYSTEM AND LANDFORM FIELD PERFORMANCE MONITORING

Performance monitoring is critical for evaluating whether a system meets performance expectations. It is impractical to develop a single rule or guideline for the details of the exact approach or how long monitoring should occur. Instead, a cover system requires a monitoring strategy that accommodates the design of the cover system, regulatory requirements, the needs of the mine operation and the stakeholders, and, most importantly, the mine closure plan. This section discusses design life and performance monitoring assessment periods, puts forth a framework for temporal and spatial-scale monitoring, and addresses cover system and landform field performance monitoring.

8.1 Design Life and Performance Monitoring Assessment Period

All engineering designs or structures, including mine closure designs and structures, are subject to failure and have associated lifespans. The design life, or life expectancy, of a product or structure is the period during which the item is expected to work within specified parameters. To maximize longevity of a cover system, the engineered landform should be incorporated into the landscape in equilibrium with its natural environment. The two largest disturbances associated with mine closure involve water balance and energy balance. The designer should address implications that re-establishing an equilibrium may have on the performance of closure landforms and associated cover systems. Understanding the required equilibrium between the closure landscape and the existing landscape also provides an indication of timescales involved. For instance, it is unrealistic to assume engineered structures will meet performance expectations following an end-member event, such as glaciation.

An "assessment period" is different than "design life." For example, MEND (2012) recommends that cover system designs use a minimum 100-year design life, and then subject the design to a risk-based assessment over a longer timeframe and on a site-specific basis. The failure modes and effects analysis approach is recommended by MEND (2012) for this task.

Assessment periods of centuries or longer may not be practical for many mines, considering the large degree of uncertainty associated with climate change projections on such scales. In cold regions where remote sites are typical, the ability to monitor performance and provide mitigating measures will be even more expensive and challenging. Nahir et al. (2012) advocate longer assessment periods for cover systems in these conditions. Consultation with several Aboriginal stakeholder groups indicated assessment periods coinciding with seven generations (to roughly 200 years) may be appropriate.

Ultimately, the selection of design life and assessment period depends on regulatory requirements, stakeholder expectations, cover system design objectives, construction materials, overall mine closure planning, and cost (Figure 8-1). Timeframes pertaining to design life should be considered in terms of, but not limited to, adequate slope stability factors of safety, adequate flow capacity for internal drainage systems, and adequate surface water management systems.

Within the closure monitoring and maintenance period (Figure 8-1), three individual management periods have been identified. The temporal end points for each of these periods is strictly site-specific and influenced by factors such as remoteness and geomorphic activity, for example. The key difference between the three management periods is the level of direct management that occurs.

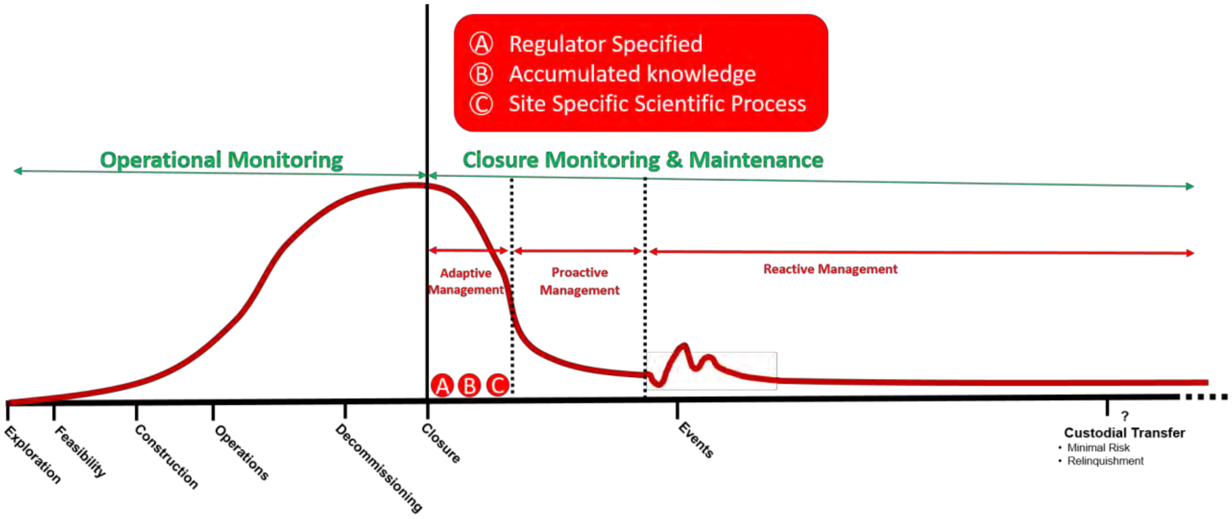

Figure 8-1. Performance monitoring framework for the assessment of cover systems with time.

8.1.1 Adaptive Management Period

An adaptive management period represents the period immediately following closure of the landform where a cover system has been employed. In some cases, this adaptive management period may include time leading up to closure where closure works are implemented during operations. An example of an adaptive management period can be the timeframe of greatest vulnerability if re-sloping of a landform is required, followed by placement of a cover system. In this case, the timeframe shortly after construction, before revegetation is effectively stabilizing the slope, would constitute one "definition" for the adaptive management period. This period represents a period in which the cover system is at its greatest risk of failure as it has its largest divergence from environmental equilibrium. For this example, this represents a timeframe when the operator will have the greatest capacity to respond, and in a cost-effective manner.

Additional examples for "defining" an adaptive management period can be developed on a site-specific basis. For example, the period representing a wetting up, or drying (in the case of tailings) of a waste storage facility following placement of a cover system (or cessation of operations). Both examples represent adaptive management periods for a site-specific "scientific" basis.

Within the adaptive management period, there are three streams of thinking, which will be left to the reader to determine for their sites:

1. Regulator specified;
2. Accumulated knowledge; and
3. Site-specific scientific basis.

Ultimately, adherence with regulator conditions will first set the period in which monitoring activities will guide adaptive management approaches. Failing imposed regulation, sites may use previous knowledge or learnings to specify monitoring timeframes for the adaptive periods. Examples of this are not just limited to operational experience, it may be a condition to incorporate monitoring or traditional knowledge to include "X number of generations". Ideally, all the approaches should be founded on a site-specific scientific basis. That is, monitoring should consider the dominant processes related or impacting environmental compliance conditions in place. This might include processes such as phreatic surface rebound in pit lakes, wetting up of waste rock piles, climax vegetation, etc.

8.1.2 Proactive Management

As site resources such as personnel and equipment are reduced and re-allocated to other projects, a more formal plan is required. During the long-term monitoring and post-closure maintenance period, it is reasonable to evaluate conditions in terms of the consequences that would ensue from events, particularly hydraulic and seismic events, of certain magnitudes. If events can produce consequences that can be repaired as a matter of course by the maintenance approach, then this represents one set of conditions. If, on the other hand, the consequences of a specific event required a substantial or complete rebuild of the originally-designed closure facilities, then a major intervention would be required, and that would be another class of risk entirely (Logsdon, 2013). A framework for repairs during this proactive management period such as that proposed by Logsdon (2013) provides a logical event triggered framework composed of sub-systems most likely to experience failures. These sub-systems can be evaluated differently depending on the engineering capability of the site and the timelines of repairs.

Therefore, a regular fixed frequency monitoring and maintenance schedule can be implemented to ensure the landform and cover system are trending along the designed trajectory. Frequency will be less than during adaptive management.

8.1.3 Reactive Management

As the term suggests, reactive management is the period when issues are rectified strictly on a reaction basis, once a trigger event occurs. It will be up to the site personnel to clearly articulate what these trigger events are and how they will be managed.

An example might be that for beyond a period of approximately 50 years, the site owner should anticipate that there will be a period of long-term maintenance and monitoring that will document that the expectations for stable slopes with controlled water quality performance have been met. In this way, trigger type events can be clearly differentiated from smaller background environmental noise, evolving the cover system in the non-detrimental way. The monitoring will therefore be focussed in response to site events and conditions, driven by what occurs on site in the relevant closure domains such as the cover system. This phase of monitoring can be triggered by such events as fires, floods, earthquakes, and other extreme events.

8.2 Framework for Temporal- and Spatial-Scale Monitoring

8.2.1 Temporal-Scale Monitoring Framework

Figure 8-2 presents a framework for rationalizing temporal-scale monitoring, as put forth by Barbour (2014). In this framework, key activities coinciding with development of a cover system for a site are highlighted, together with general timeframes. Figure 8-2 summarizes these key activities and timeframes.

The framework presented in Section 2 and summarized in Table 6-1 offers guidance on three key components of design to cover system designers. First, the general sub-activities, or objectives, for each of the key activities are noted. This provides the opportunity for designers and owners to align site- and project-specific objectives with general cover system design objectives. In this case, design details for the performance monitoring system can be developed to meet these objectives. Second, timeframes for key design activities are presented so that designers and owners have a reasonable timeframe typically required for cover system development.

Finally, a rationale for the key activities that tend to involve longer timeframes is provided. For example, a typical question is: How long should one monitor cover system field prototypes, and why? Figure 8-2 and Table 8-1indicate that this timeframe could be developed to capture more frequent climatic cycles and to develop field performance monitoring data that span, to the greatest extent practical, the range of climate conditions at site over as short a time as possible.

For long-term monitoring, the objective is to verify design properties and processes, and monitoring timeframes could be based on capturing less-frequent climatic cycles (e.g., Pacific Decadal Oscillation). Finally, as long-term monitoring moves into timeframes of greater than 10 to 20 years, the objective becomes one of closure assurance and tracking the evolution of the landscape.

Table 8-1. Summary of key activities and timeframes for cover system development (after Barbour, 2014).

Key Activity	**Timeframe(s)**
1. Establish design objectives	• Months
2. Characterize available materials	• Months to years
3. Develop design alternatives o Modelling ▪ Analytic, spreadsheet, numerical	• Months to one (1) year
4. Cover system field trials o Construction of field trials o Monitoring ▪ All elements of water balance ▪ Evolution of cover materials o Data interpretation and analysis ▪ Complete water balance ▪ Identify controlling mechanisms/process	• Three (3) to five (5) years: o As per section 3.6 on climate variability o Objective is to capture more frequent climate cycles: ▪ e.g., El Niño/La Niña cycles o Research shows that cover materials evolve (i.e., their hydraulic properties evolve) in the 3 – 5-year period following placement
5. Full-scale cover system construction	• Months to years
6. Long-term monitoring o Verification of design properties and processes o Tracking evolution of landscape with time	• Ten (10) to twenty (20) years o Cover system performance ▪ e.g., Pacific Decadal Oscillation • Twenty (20) to 100+ years o Closure assurance ▪ As per corporate, regulatory and stakeholder commitments

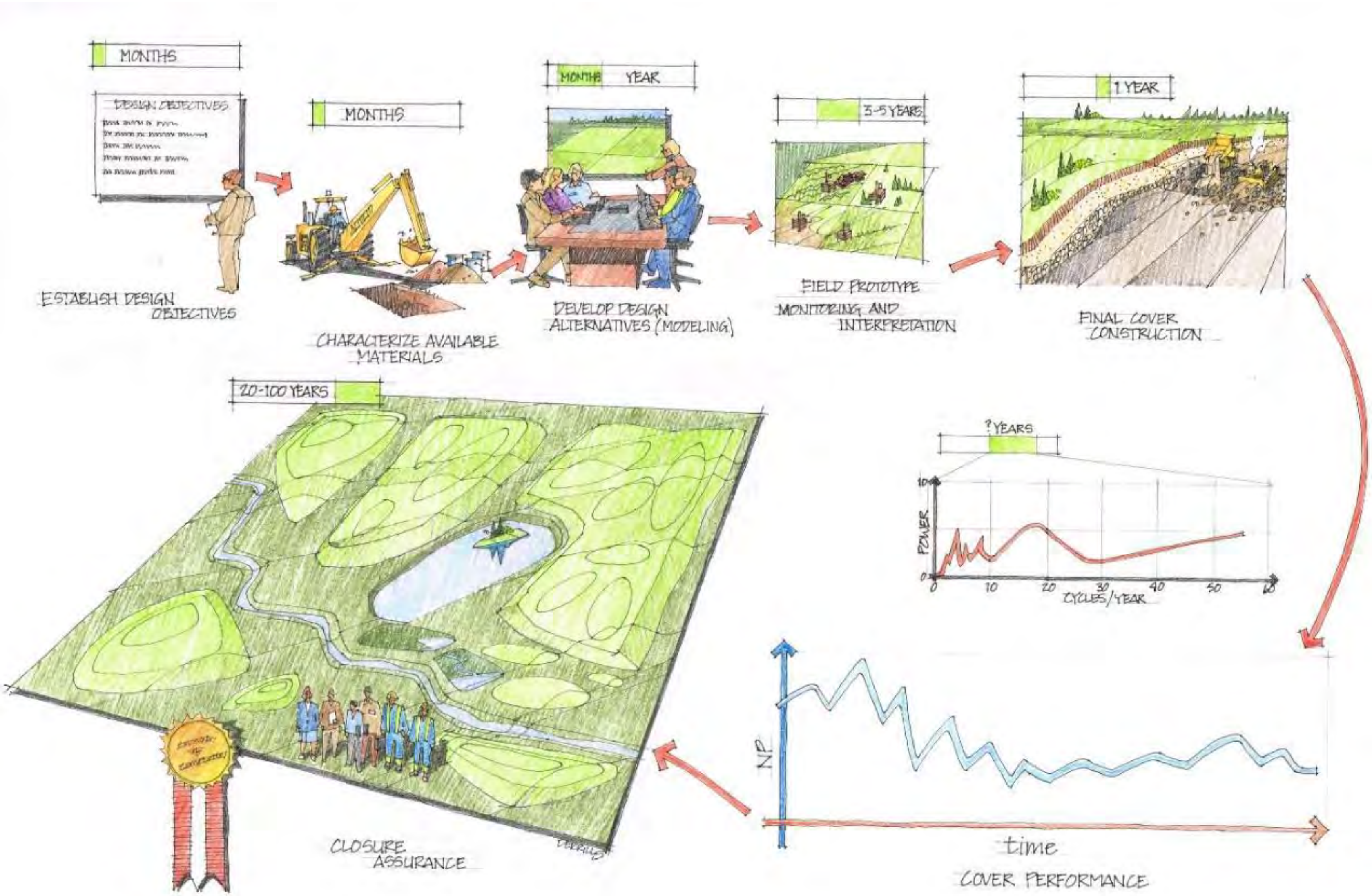

Figure 8-2. Framework for temporal and spatial-scale monitoring.

8.2.2 Spatial-Scale Monitoring Framework

Figure 8-2 can also be used to develop an understanding of spatial-scale monitoring requirements for cover systems. The approach builds on Barbour *et al.* (2004), and McKenna *et al.* (2011). These studies discuss the advantages of utilizing a watershed approach for cover system field performance. In practice, this implies a focus on studies that encompass at least one complete watershed within the landform.

Within this watershed, which might be in the range of a few and up to 10 hectares (or even 100 hectares), a site should document the watershed mining and reclamation history, characterize the substrates and develop a full-water balance (McKenna *et al.*, 2011). Then, prototype cover system field trials of a few to multiple hectares, if the project allows, can be situated within this watershed. Understanding and documenting the history and processes (particularly those involved with water and ionic balances) provides the necessary basis for moving from one spatial-scale to the next.

Barbour *et al.* (2004) provide several reasons for a watershed approach:

- It is the primary unit for mine planning, particularly as it relates to routing of surface water;
- It is of sufficient size to address central questions about landscape performance and risk, while encompassing a range of target ecosites for a parent material;
- It allows for realistic measurements and estimates of essential fluxes and balances (e.g., water, salt (oxidation products), nutrients);
- It includes sufficient complexity so that the complex interactions between these fluxes are represented; while
- At the same time keeping monitoring and analyses manageable.

A site moves through both temporal- and spatial-scales (Table 8.1), moving from research, through to development, and finally the commercial scale. Initially, steps 1, 2, and 3, as presented in Table 8.1, could represent the research aspect of a project. In this context, mine operators can pose questions such as: “What cover material thickness meets the site’s risk profile for achieving closure objectives?” or “What cover soil thickness will minimize the risk of adversely affecting water resources due to solute transport from the waste storage facility over 100 years?” Cover system designers would address more specific questions with the same work, such as: “Does layering affect moisture movement in the cover soil?” or “Can increasing water holding capacity increase the potential for meeting reclamation objectives?”

Given these and other questions, within the spatial- and temporal-scales noted in steps 1, 2, and 3 of Table 8-2, and as the site "upscales" to the next steps, understanding long-term performance is essential. For example, using large mining equipment to place reclamation material, and the inherent variability of the resulting soil profiles, can be much different than what laboratory column tests and pilot-scale field trials suggest. Real-world application may involve substantial changes to the initial plan, or even, in some cases, abandoning promising cover systems as impractical.

Table 8-2, building from the information in Table 8-1 and utilizing the approach presented by McKenna *et al.* (2011), summarizes the different spatial-scales, activities and objectives of developing a cover system design.

8.3 Full-Scale Field Performance Monitoring

Where possible, full-scale cover system performance can be evaluated by water quality and quantity analyses of seepage discharged from the waste storage facility. This approach empirically describes a waste storage facility through monitoring of its cumulative effect at the base. This technique can simplify monitoring and optimizing costs by using available drainage outlets (e.g., a river, a lake, or a groundwater well). The measured results, meanwhile, provide direct information for comparison with the design criteria or other water quality guidelines.

Monitoring the cumulative effect at the base of the waste storage facility using seepage water quality and quantity has two major disadvantages. First, it may take tens if not hundreds of years before a considerable change is measured inside or downstream of the waste storage facility due to, for example, drain-down effects, complete oxidation of sulphidic minerals, and/or mixing with groundwater. Second, without additional forms of monitoring, there will be insufficient information to explain results that fail to meet expectations. An understanding of measured water quality at the base of a waste storage facility does require some fundamental parameters, including precipitation, runoff, and water storage change. But this monitoring approach on its own does not provide enough information for understanding and demonstrating performance of a cover system placed on the waste storage facility to mitigate ML/ARD.

Table 8-2. Summary of key activities, scales and objectives for cover system development (adapted from McKenna et al., 2011).

Stage, or Timeframe (Table 8-1)	Scale	Activities	Objectives
1. Establish design objectives 2. Characterize available materials 3. Develop design alternatives	- Desktop, bench/laboratory/greenhouse scale	- Develop a series of specific cover system design alternatives - Aimed at gaining a better understanding for site-specific climate, materials and conditions	- Focuses on understanding and assessing different alternatives and the potential upside of the different cover system alternatives - Ideally, tied to economics, but recognition that more detailed analysis is required
4. Cover system field trials	- Pilot	- Involves a promising, or series of promising cover system alternatives that has (have) moved from the first three stages and is ready to be tested at a field scale - Typically, many orders of magnitude greater in size than practical in the laboratory	- Focuses on scale-up and performance under continuous operation, and includes environmental and economic assessments - Aims to identify fatal flaws
	- Prototype	- Prototype field trials are permanent and constructed using commercial-scale equipment, while being large enough to gain confidence to move to commercial-scale - Designed to allow optimization for commercial-scale, to fit into mining and closure plans, receive regulatory approval	- Focuses on testing at full-scale, developing parameters, and optimizing design for commercial operation - Gains commercial-scale experience for operators
5. Full-scale cover system construction 6. Long-term performance monitoring	- Full-scale	- Involves normal closure activities running at full-scale for several years	- Focuses on functioning safely, reliably, cost-effectively, and with continuous improvement; all while meeting closure objectives

8.3.1 Direct Field Performance Monitoring

Direct cover system field performance monitoring should be considered state-of-practice, such that it augments monitoring of cumulative effects at the base of the waste storage facility using seepage water quality and quantity data. In addition, direct field performance monitoring can be implemented during the design stage with cover system field trials, or prior to completion of the full-scale cover system. This allows for gathering monitoring information prior to the cumulative effects being influenced by the presence of the cover system.

Utilizing a direct cover system measurement approach provides the opportunity to begin tracking the trajectory of cover performance and compare this trajectory to predicted performance. The objective is to determine if performance is on track to meeting expectations, prior to observing the full influence of the presence of the cover system for the mine waste landform. This offers an opportunity to minimize the frequency and extent of monitoring as the site moves through the long-term cover system monitoring time scale. In addition, during earlier time scales, the direct cover system monitoring approach can be used to adaptively manage cover system design, by applying lessons learned from monitoring to future cover system design and construction.

The overarching general objectives of direct cover system field performance monitoring (adapted from MEND, 2004) are to:

- Obtain a gas, heat, mass, and water balance for the mine waste landform;
- Develop or enhance understanding for key characteristics and processes that control performance;
- Develop a set of field data to calibrate a numerical model (which can be used to adaptively manage cover system design moving forward within the design development time scale); and
- Develop confidence with all stakeholders with respect to cover system performance.

The objectives of direct field performance monitoring can be achieved by monitoring multiple components of the water balance such that key indicators of performance (e.g., net percolation) can be understood with the highest possible degree of confidence. Figure 8-3 illustrates the components of the heat and water balance that should be monitored when directly monitoring performance for pilot and prototype field trials. As the site moves through the temporal- and spatial-scales of cover system development, the recommended minimum level of monitoring for full-scale cover systems includes meteorological monitoring (PET), site-specific precipitation, cover material moisture storage and temperature changes, watershed or catchment area surface runoff, vegetation, and erosion. Monitoring should capture the entire system from climate, soil-atmosphere-plant, landform load and water balance, groundwater and surface systems.

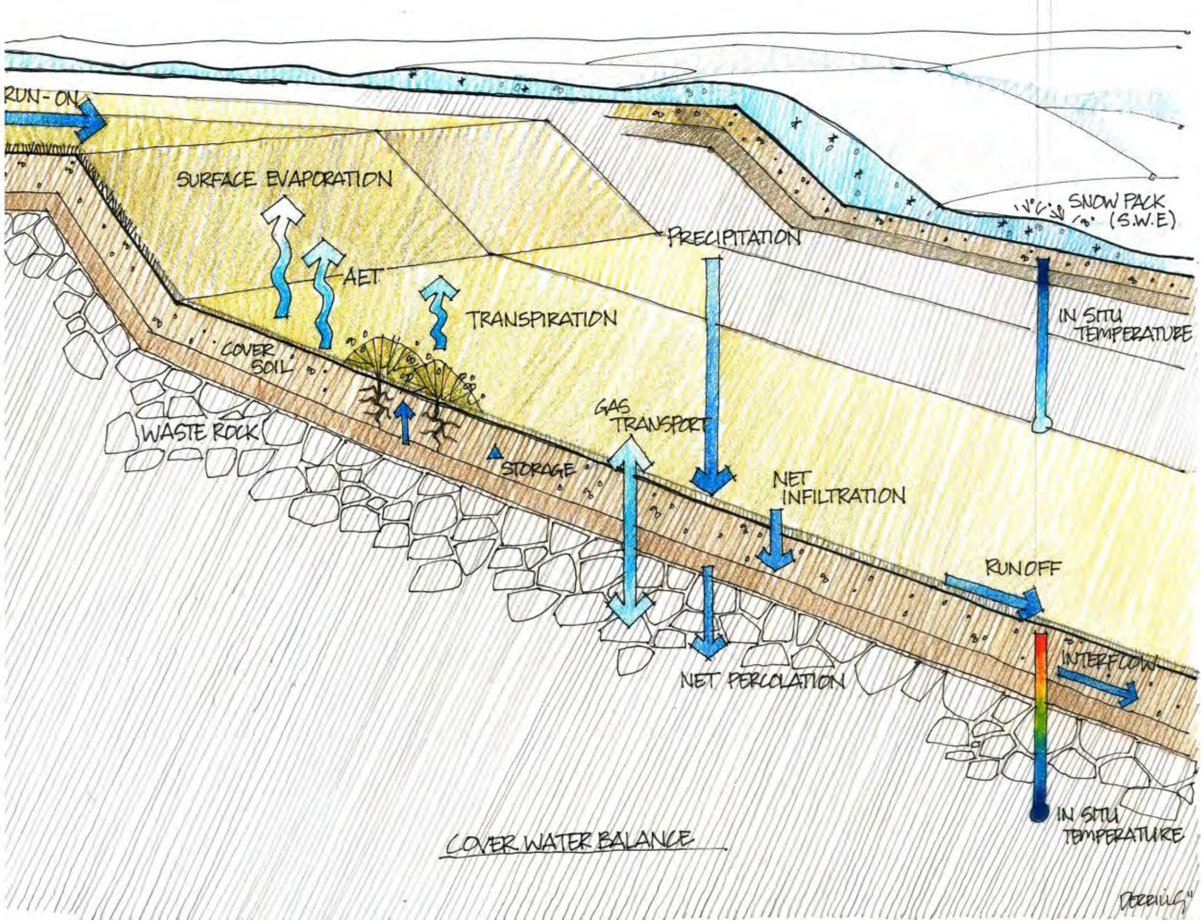

Figure 8-3. Conceptual schematic of the components of a direct cover system field performance monitoring system.

8.3.2 Specifics on Direct Cover System Field Performance Monitoring

An example of direct cover system performance monitoring on a prototype to commercial scale is illustrated in Figure 8-4, which captures the potential influences on performance from a spatial perspective from the top of the waste storage facility down the slope of the facility.

This sub-section presents specifics associated with direct cover system field performance monitoring. More detailed information on each monitoring component noted in Figure 8-3 and Figure 8-4 can be found in the *Macro-Scale Cover Design and Performance Monitoring Manual*, prepared for MEND (2007).

8.3.2.1 Surface Hydrologic Monitoring

Hydrologic monitoring involves measuring and tracking the movement of water in the watershed. Surface hydrologic monitoring includes precipitation, runoff, pond monitoring, and evapotranspiration. These processes are illustrated in Figure 8-3.

Precipitation: Precipitation includes rainfall and snowfall. Rainfall should be measured at several locations on a watershed to quantify spatial differences in rainfall volume and intensity. Snowfall could be measured with an all-season precipitation gauge. At a minimum however, regular depth/density measurements of the snowpack should be collected with increasing frequency as spring freshet approaches. The three most common methods for the measurement of precipitation are: non-recording gauges; recording gauges; and a snow survey.

Runoff**:** A watershed is an area of land that contributes runoff to a single outlet location; hence, it can be determined by measuring stream flow from the outlet of a watershed. Stream flow is typically measured using either velocity measurement or stage measurement (McCuen, 1989). Velocity measurement is best suited to large rivers or permanent streams in which the flow rates are more constant. Stage measurement can either use the natural streambed, or it can involve construction of measurement structures. Flow rate measurement structures are the most common method used in small, ephemeral streams and are therefore the most practical for small watersheds. These structures have a known stage-discharge relationship, which can be applied without detailed measurement of the stream flow. Weirs and flumes are the most commonly used structures in runoff measurement applications.

Pond Monitoring**:** Typical pond monitoring consists of collecting water level and seepage data. Evaporation is usually evaluated using meteorological data. Water level measurement is conducted using a staff gauge or some other type of manual depth measurement. Seepage meters are the most commonly used method for direct measurement of seepage. Seepage meters range from simplistic manual devices to complex automated devices. In typical watershed pond applications, the simple barrel and bag-type seepage meter typically gives suitable results for water balance determinations.

Evapotranspiration: Atmometers, evaporation pans, and weighing lysimeters are widely used to directly measure both evaporation and evapotranspiration. The most commonly used micrometeorological tools are the Bowen ratio energy balance method, the aerodynamic method, and the mass transport method. Eddy covariance, which measures evaporative flux from the surface, is perhaps the most useful micrometeorological method.

8.3.2.2 Sub-Surface Hydrologic Monitoring

Sub-surface hydrologic monitoring involves measuring and tracking the movement of water through the various soil layers of the watershed, which includes measurements of soil water content, soil suction, net percolation, interflow, soil temperature, and field hydraulic conductivity.

Soil Water Content: Measurements of water content are essential to the development of a water balance for a watershed. Water content profiles in the waste and cover layers allow the volume of water stored within the profile to be quantified and can be interpreted to define the rates and direction of water movement in response to plant root uptake, evaporation, percolation, and interflow. The five most common methods of measuring *in situ* water content of soils are: gravimetric; nuclear; time domain reflectometry (TDR); frequency domain reflectometry (FDR); and electrical capacitance. The latter three methods are preferable, given that they can be automated and connected to a data-acquisition system such that real-time responses to field performance can be measured. Care must be taken to properly calibrate these sensors to field conditions to obtain quantitative measurements. In addition, the response of these sensors to *in situ* salinity varies among different manufacturers, and therefore caution is required to ensure that the sensor chosen is compatible with the anticipated *in situ* conditions.

Soil Suction: The three most common tools to measure soil suction in the field are: tensiometers; thermal conductivity sensors (or heat dissipation sensors); and electrical resistance sensors (gypsum blocks). All three provide a field measurement of matric suction, which, along with osmotic suction, are the two components of total suction. This document recommends thermal conductivity sensors as the most appropriate tool for cover system monitoring. They are automated, robust, and generally do not degrade over time. However, an understanding of anticipated *in situ* matric suction conditions is required, given the operating range of typical thermal conductivity sensors. In coarser-textured materials, the use of tensiometers should be considered, as they can be more accurate at low levels of suction. Gypsum blocks also measure low suction, with 200 kPa as the upper limit of precision.

Net Percolation: Net percolation is a critical component of the water balance for a cover system and/or landform and a key performance indicator for cover systems placed over reactive waste. In addition, owing to the simplicity of its application (as a percentage of precipitation), it often helps stakeholders gauge closure performance.

Figure 8-4. Conceptual schematic of a direct cover system field performance monitoring system for a mine waste landform.

Direct and indirect approaches are available for determining NP rates. A common indirect method is the water balance approach. In this case, measurements of *in situ* water content conditions, surface runoff, and ET are used to back-calculate NP. One disadvantage of this approach is the relative size (and associated errors) in the measurements of precipitation and/or ET relative to the magnitude of NP. A second potential disadvantage is that the change in water storage measured at a single location will not be representative of the entire cover system. Differences will result due to the variability of cover material, as well as *in situ* density. The variability in meso-topography and vegetation across the cover system will also affect *in situ* water content. To address this issue, multiple *in situ* water content profile monitoring locations should be installed, such that the variability due to the above noted factors is understood, and the multiple lines of evidence are included in the water balance calculation. In essence, two key components are being measured on two different scales. Runoff is inherently a macro-scale, or watershed measurement, while measurements of *in situ* water content are typically viewed as micro-scale, or point-scale measurement.

Using a single moisture water content sensor profile to measure both water balance and runoff within a watershed (i.e., the cover system) poses challenges. However, measurements of *in situ* water content conditions should be taken at multiple locations within the watershed, such that the range of moisture conditions within in the watershed (i.e., the cover system) can be incorporated into the water balance evaluation. Unlike most other parameters, an additional potential challenge is the relatively low resolution of surface runoff measurements, compared with that of other parameters. If the measurement resolution of surface runoff is within the range of NP rates that one is attempting to back-calculate, it can be difficult to use the water balance method. This may occur in the case of cover systems designed for very low NP rates.

It is also possible to back-calculate NP rates for a cover system by calibrating a soil-plant-atmosphere model to measure *in situ* water content conditions and surface runoff, using the measured climatic conditions as a model input.

One method for determining cover system net percolation rates is to directly measure it using one of three types of lysimeter techniques: weighing lysimeters; zero-tension (or gravity-drainage) lysimeters; and tension lysimeters, all illustrated in Figure 8-5. In terms of monitoring cover system performance, gravity-drainage lysimeters are the most common.

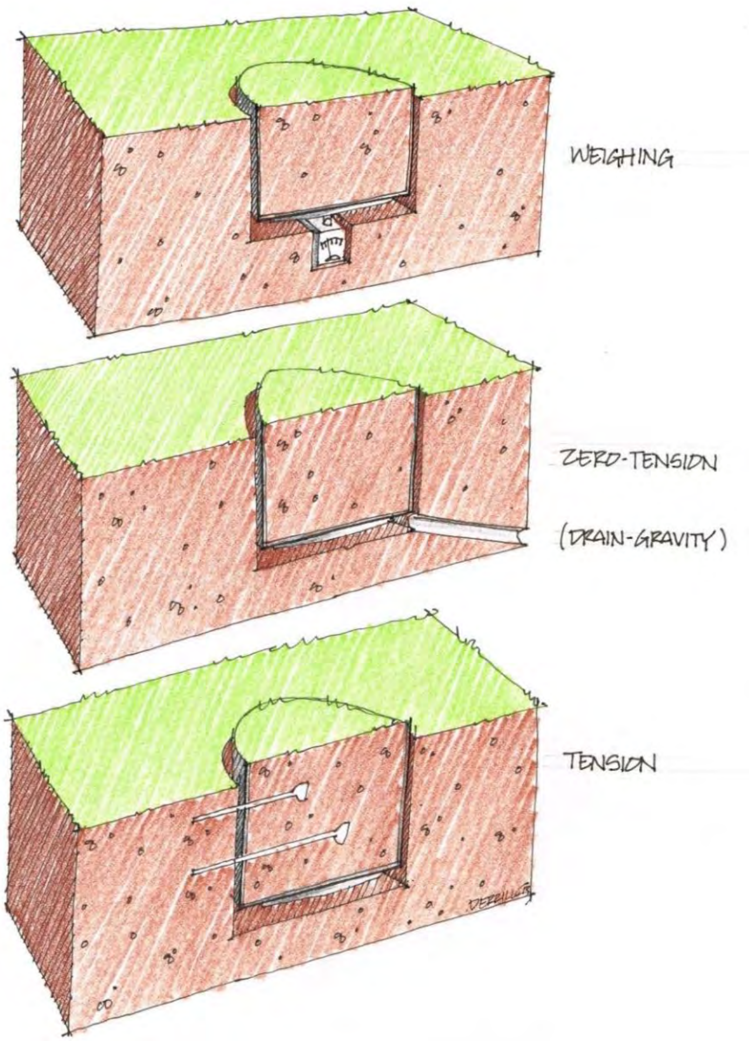

Figure 8-5. Schematic illustration of direct measurement lysimeters (weighing, zero-tension, and tension lysimeters).

A lysimeter is essentially a large tank (e.g., 2.5 m diameter by 3 m deep), or a lined facility (e.g., 10 m by 10 m) placed within the underlying waste below the cover system in which percolation is collected at the base, and then directed toward an underdrainage and measurement system. It can be difficult to install a lysimeter because, depending on anticipated NP rates and *in situ* hydraulic properties of the waste material, the lysimeter may need to be constructed to a depth where it is unsafe and impractical to install. Placing a lysimeter on a steeply sloping surface introduces additional construction and safety challenges.

The areal extent required for a lysimeter is highly site-specific. For example, the size should allow for full-scale cover system construction equipment to be utilized for placement of the overlying cover material. Abichou et al. (2006) argued that a lysimeter should be at least 7 m wide and be twice as wide. Abichou and Musagasa (2008) state that the length and width of a lysimeter should be five times larger than its depth. Benson et al. (2001) recommend that a lysimeter be at least 10 m wide and 10 m long to account for the inherent variability in the overlying cover material and ensure a "bulk" net percolation rate is measured. The primary rationale for a larger lysimeter is the inherent spatial variability of a cover system. This variability will result from placement of the cover material, which will affect the as-built hydraulic conditions (e.g., density and material characteristics), as well as the physical, chemical, and biological processes that influence performance of the cover system following construction (INAP, 2003). Examples include preferential flow (macro-features), vegetation, and material evolution.

For small-scale lysimeters (e.g., ~0.3 m in diameter), one should expect high variability in the NP measured. Increasing the number of these small-scale lysimeters would provide an understanding of the variability of cover system performance, which is a positive aspect for understanding performance, but does result in challenges with determining a representative NP rate. A larger-scale lysimeter will reduce the variability being measured with the objective of obtaining a measure of the bulk net percolation for the system. Whether the variability has been captured will depend on the site. The areal extent of a lysimeter is often a function of constructability (practicality, safety, and cost), coupled with the level of comfort required to capture the inherent cover material variability.

While the measurement principal of a lysimeter is conceptually simple (i.e., collect water at a depth below the cover system and compare to precipitation), properly designing, installing, and operating one is not simple. Data from lysimeters used for measuring net percolation from a cover system should be interpreted with caution and the lysimeter should supply a representative measure of field performance. This is because the depth of the lysimeter, and as a result the lower boundary condition at this depth below the cover system, influences the net percolation; the same pore-water pressure regime within the lysimeter does not reflect conditions outside the lysimeter. A detailed discussion of this issue with respect to lysimeters is not within the scope of this document. O'Kane and Barbour (2003) explored the subject and put forth a methodology for properly designing a lysimeter to ensure the presence of the lysimeter minimally influences the NP being measured.

Interflow*:* Quantification of interflow is important for evaluating cover system water balances in conditions where lateral flow in the cover system may occur (e.g., over the top of a geomembrane, at a textural contrast, etc.). This lateral flow can affect stability of the cover system (erosional and geotechnical) if there is insufficient lateral drainage capacity. It can also lead to "breakthrough" of net percolation as pore-water pressure in the overlying cover layer increases due to infiltration from above combined with lateral seepage. In addition, it is useful to understand the contribution of interflow as seepage into swales or ponds in the watershed. The layout of an interflow monitoring system would be dependent on the topography and drainage patterns of the watershed. For example, a single weeping tile drain may be installed in a given area, with the drain aligned parallel to the topographic contour of the area, so that it runs perpendicular to the flow of water. Monitoring the interflow rate depends largely on the quantity of interflow and the resolution of measurements required.

Groundwater: Perched water tables and groundwater flow add complexity to large-scale water balances. The most common method of monitoring groundwater levels is with a standpipe piezometer, usually a PVC pipe with a lower screened or slotted portion that allows water to flow in. The difficulty associated with groundwater monitoring for watersheds on reclamation material is that significant changes in material layers can create a complex sub-surface hydrology. Historic practices of disposing of refuse or old equipment in pits or waste rock dumps can pose a problem when trying to drill through the material.

Soil Temperature: The temperature of the soil profile defines the presence of freezing conditions, provides an indication of geochemical activity, and highlights critical temperatures for plant germination and growth. Measurement of soil temperature is relatively straightforward: a sensor is either permanently buried or temporarily inserted in the soil at the depth of interest and the temperature is measured. The most commonly used sensors for measuring soil temperature are thermocouples, or thermistors. For watershed temperature monitoring, the depths of the sensors depend on the information required and the materials and layers present. Shallow sensors are useful for evaluating biological and vegetation activity in the topsoil. Deeper sensors should be spaced according to material layers, such as in layered cover systems. The depth of the deepest sensor would most likely correspond to the average depth of frost penetration. If the waste is reactive, deeper sensors may be required to monitor potential heating of the waste material (and the impact of this heat source on cover system performance).

Field Hydraulic Conductivity: Determining field hydraulic conductivity (k_{fs}) is fundamental for gauging watershed performance because secondary structures such as cracks, worm holes, root channels, macropores, etc. can provide preferential flow paths in finer-textured materials during high infiltration events. Freeze-thaw and wet-dry cycles, as well as biological activity, all contribute to soil structure development. Field hydraulic conductivity measurements are single-point; to determine a representative value, several measurements over a representative area are required.

Various methods exist for measuring soil k_{fs}, including the double-ring infiltrometer, a Guelph permeameter (GP), a tension infiltrometer, etc. The different methods each have advantages and limitations, and selection of a method should be based on the requirements of the specific application. *In situ* methods, which incorporate a large cross-sectional area, will tend to mask regions of low hydraulic conductivity. Values of k_{fs} measured with the GP typically show relatively high coefficients of variation, indicating sensitivity to the heterogeneous hydraulic characteristics of soil. These methods are based on determining water permeability; there are also methods based on determining air permeability (Rodger, 2007).

8.3.2.3 Monitoring Locations and Sensor Placement

Reclamation landscapes and the resulting watersheds are topographically and geologically complex by their very nature, and consequently can have complex hydrology. Soil water conditions, runoff rates, and evaporation and transpiration rates may be strongly tied to slope position and aspect. The biggest challenge in watershed monitoring is determining where and how frequently to monitor.

Generally, the following details should be taken into consideration when installing a watershed monitoring system.

- *In situ* water content and soil suction sensors should be installed throughout the cover/waste profile, and concentrated around interfaces in the profile (e.g., cover-atmosphere interface, growth medium layer-barrier layer interface, barrier layer-waste material interface).
- *In situ* water content and soil suction sensors should be installed adjacent to one another to facilitate the development of "field-based" water retention curves and hydraulic conductivity functions for each layer in the cover/waste profile.
- A watershed monitoring program should have one or two detailed or primary instrumentation sites along with several secondary monitoring sites. For example, a primary instrumentation site may include automated *in situ* water content and suction sensors, an access tube for manual *in situ* water content measurements, *in situ* gas sampling ports, a lysimeter, and a fully automated meteorological station. A secondary monitoring site may only consist of a volumetric water content sensor profile, or at least an access tube for manual measurement of the *in-situ* water moisture conditions. This will give some indication of the potential spatial variability of conditions in the watershed.
- The locations of primary and secondary instrumentation sites should reflect the varying conditions influencing performance of the watershed. For example, if slope orientation is thought to strongly influence evaporation and vegetation conditions, more than one slope aspect should be monitored. Other factors that can influence the location of a monitoring site include slope angle, runoff and run-on conditions, slope length, elevation of the monitoring location, meso-topographic conditions, reactivity of the underlying material, and texture of the underlying material.

8.4 Addressing Challenges with Temporal- and Spatial-Scale Monitoring

Barbour (2014) notes that within the timeframe for cover system field trials (Table 8-1), challenges arise because the timeframe is often project-driven, compared with the ideal of being driven by climate cycles. In addition, monitoring is often conducted at small spatial-scales, typically on the order of several square meters or less (albeit at several locations), which is just 1/10,000th of a 1-ha cover system field trial. This raises the questions of how many locations must be monitored, and at what scale, to ensure that performance of the cover system as a whole is understood?

8.4.1 Utilizing Point Scale Measurements to Evaluate Full-Scale Performance

Tallon (2014) utilized the Hilbert-Huang transform (HHT) technique to separate different scale processes and identify location-specific scale variation of non-stationary and non-linear soil spatial variability. HHT is a two-step method to analyse spatial variability of datasets obtained from a point-scale monitoring system. Application of HHT to the spatial variability analysis requires field-measured data at the different locations. Alternatively, soil-plant-atmosphere modelling could be conducted with a sensitivity analysis on key cover system conditions that would be expected to influence performance on a spatial-scale (e.g., meso-topography, vegetation, *in situ* permeability, *in situ* water retention characteristics). HHT analyses can then be conducted on the model outputs and once some understanding for spatial variability of the above noted conditions is developed, the scale over which monitoring of the cover system should occur can be determined.

The closer the monitoring locations, the more similar the datasets should be. Measurement of *in situ* moisture conditions in a cover system over these different scales can be achieved using volumetric water content sensors, temperature sensors, and/or through other geophysical techniques (e.g., ground penetrating radar). These spatial-scales can be employed to guide and/or adjust performance monitoring in a macro-scale (full-scale) cover system, once the dominating spatial-scales are determined from analysis of the datasets obtained from point-scale measurements on a field trial. In this way, the field performance monitoring system should provide a representative measure of cover system performance.

8.4.2 Non-Conventional Techniques to Evaluate Full-Scale Performance

Barbour (2014) discusses monitoring approaches to track water balance and migration within closure landforms over large spatial- and temporal-scales. Methods discussed include the use of air-permeability testing, geological weighing lysimeters (GWL), distributed temperature sensing (DTS) using fibre optics, mapping stable isotopic composition of site wide waters, and deep profiling of the stable isotopes of water.

Table 8-3 (from Barbour, 2014) summarizes these methods and the parameters measured, as well as some key positive and negative aspects of each method in terms of spatial- and temporal-scale monitoring. No single method will address all temporal and spatial monitoring objectives. However, each has key aspects that offer promising alternatives to, and/or can augment, conventional direct field performance monitoring. For example, groundwater levels (GWLs) can be used to track water balance changes over a large spatial extent (e.g., a large mine waste landform) using existing technology. As a site moves through the temporal-scale of cover system development outlined in Table 8-1, when spatial monitoring scales should increase, GWLs offer a potential solution for long-term performance monitoring in addition to, or as a replacement for, point-scale direct cover system field performance monitoring.

8.5 Maintenance of Monitoring Systems

All cover systems will need repairs and maintenance. The frequency and amount are site-specific and depends on the approach put in place to balance initial design and construction costs with short- and long-term maintenance costs.

Ideally, the goal is for all maintenance to be initially focused and adaptive, with frequency decreasing over time when the cover system will be relatively maintenance-free. This is often thought of as being for the "short-term", and long-term", respectively. However, caution is warranted as these two terms are very subjective, and definition of each requires an appropriate balance of site-specific needs, as well as risk assessment using the site's risk profile. Nevertheless, common short-term maintenance activities include repair of erosional features, re-establishment of drainage channels and ditches, application of additional revegetation and/or fertilization treatments, and the repair and maintenance of performance monitoring equipment. In general, longer-term maintenance should include cleaning out drainage channels of sediment and vegetation and repairing erosion damage until the landform reaches equilibrium. Geotechnical stability audits should be completed on a regular basis. Water sampling should be completed for both surface and groundwater on a frequency that meets stakeholder and regulatory commitments.

Table 8-3. Summary of non-conventional monitoring techniques to evaluate full-scale performance (after Barbour, 2014).

Method	**Measured Parameter**	**Extended Temporal-scale** **☑: positive** **☒: negative**	**Extended Spatial-scale** **☑: positive** **☒: negative**	**Literature**
Air Permeability (spatial variability)	Air conductivity	☒ Repeated testing is required to map changes over time	☑ Greater surface area can be covered in less time as compared to water permeability testing	Rodger, H.A. (2008)
DTS (spatial variability)	Thermal properties (water content)	☒ Repeated testing is required to map changes over time	☑ Spatial variability (1 m resolution over 1000s of meters)	Tallon, L. (2014)
Geo-Lysimeter (Integration over space)	Surface water loading	☑ Relatively low cost long-term monitoring	☑ Large average area of influence (100s of meters)	van der Kamp et al. (2003) Anochikwa et al. (2012) Tipman, J. (2014)
Stable isotopes of water (Integration over time)	Deuterium and O^{18}	☒ Repeated testing is required to map changes over time ☑ Monitoring can be completed using existing water and gas sampling wells ☑ Data can be used to assist interpretation of CPT, TDR, and gas sampling profiles	☑ Deep profiles ☑ Integration of net percolation over long periods of time	Hendry et al. 2011 Baer, T. (2014) Pratt, D. (2014)

9 LESSONS LEARNED

As a summary of this guidance, available literature at time of publication and the field experience of the authors, the list below represents the most common and important aspects of cover system design that are required to ensure a greater possibility of a successful performance result. The top six lessons learned for cover system design are as follows.

1. Clearly defined and communicated cover system objectives that are developed from site-wide closure objectives.
2. Adequate/appropriate characterization of site-specific climate conditions.
3. Development of a conceptual model for current conditions and future cover system performance for the landform, including basal flow conditions, surface water management requirements, and the potential for surface disruption.
4. Adequate/appropriate characterization of borrow materials required for construction of cover system (i.e., locations, volumes, and permitting).
5. Transparent understanding of cover system performance expectations, as measured against site-specific human health and safety, risk, cost, and end land use.
6. Adequate/appropriate construction quality control and assurance for the cover system and landform.

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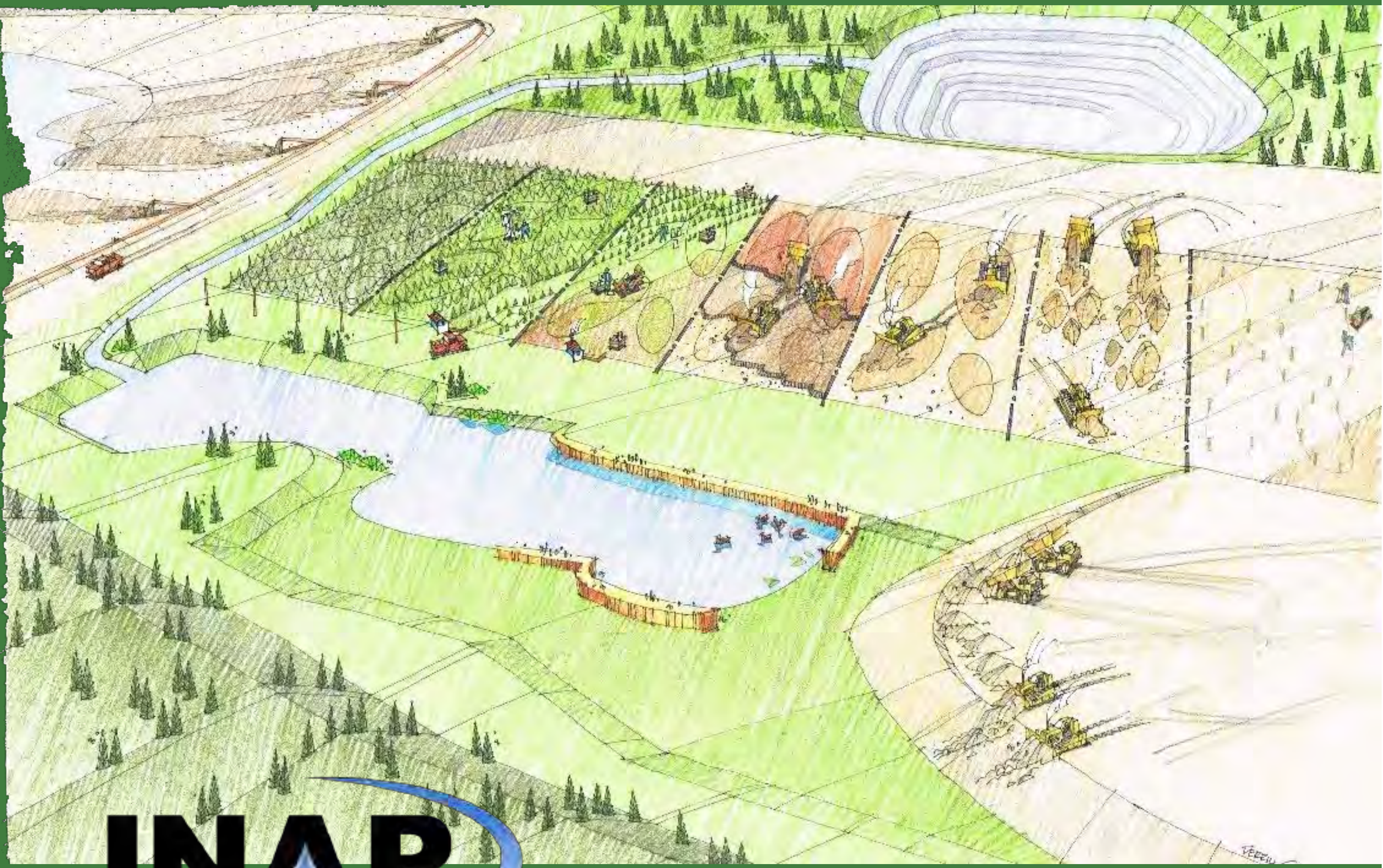
GLOBAL COVER SYSTEM DESIGN

APPENDIX A: COVER SYSTEM TOOL



INAP International Network for Acid Prevention

NOVEMBER 2017

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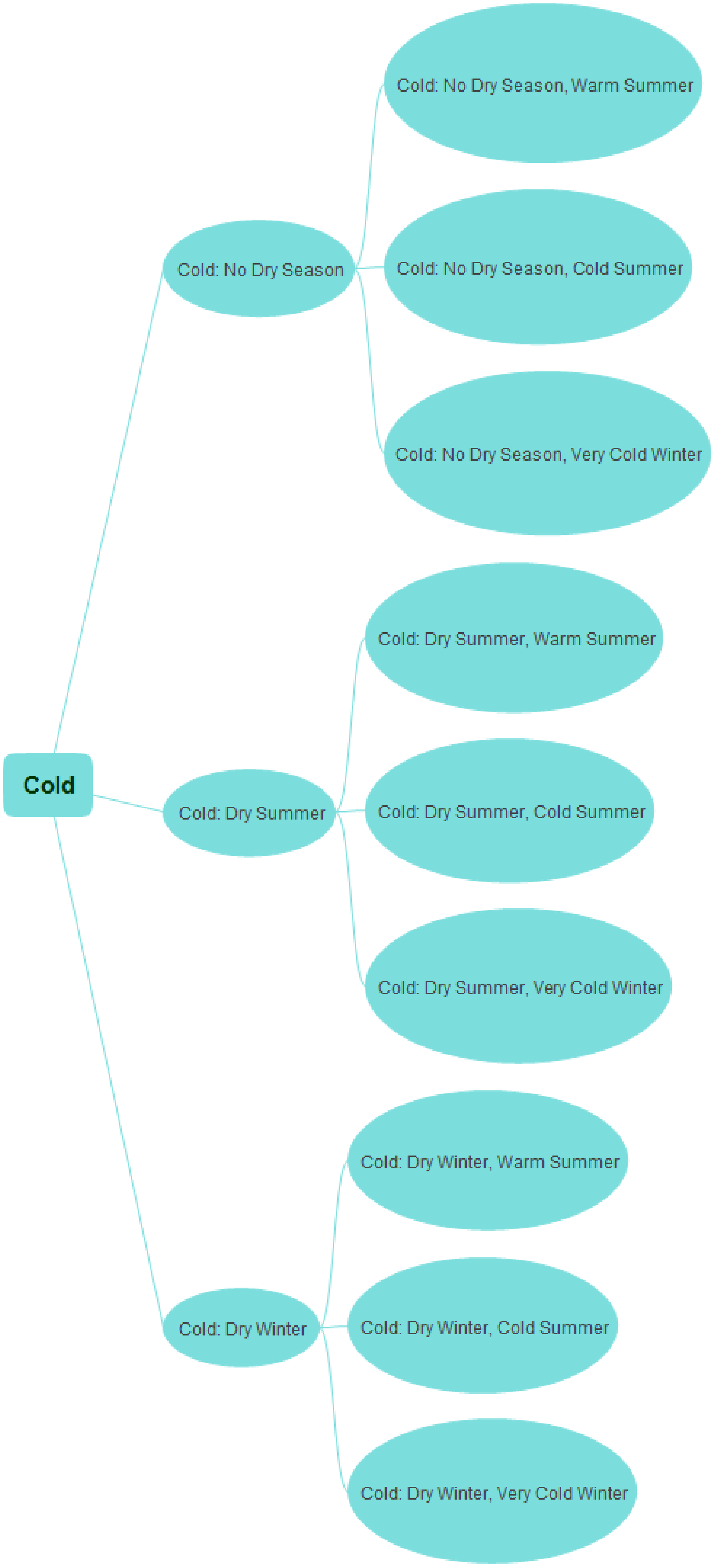
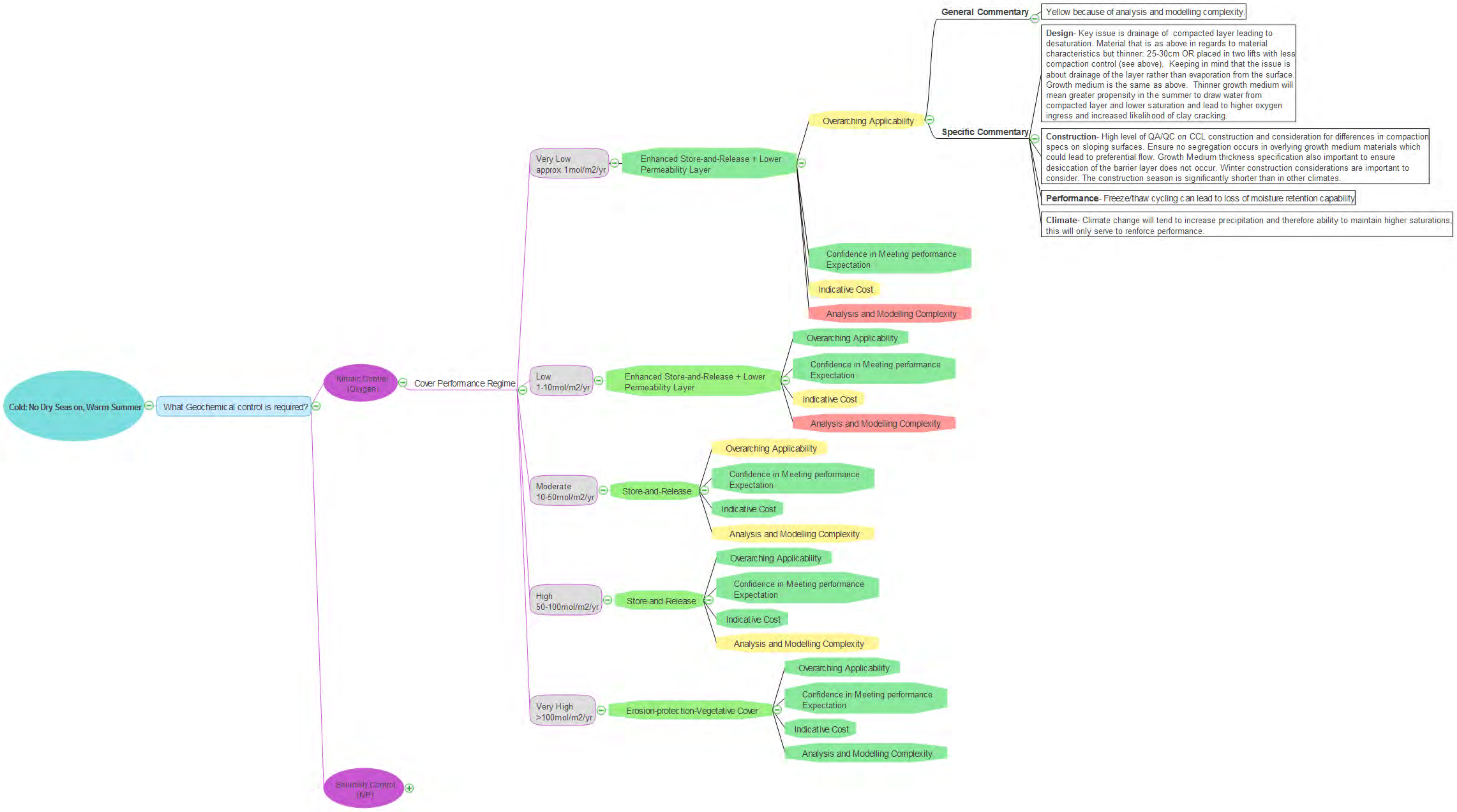
1 COLD CLIMATE OVERVIEW



1.1 Cold: No Dry Season, Warm Summer (O_2)



Yellow because of analysis and modelling complexity.

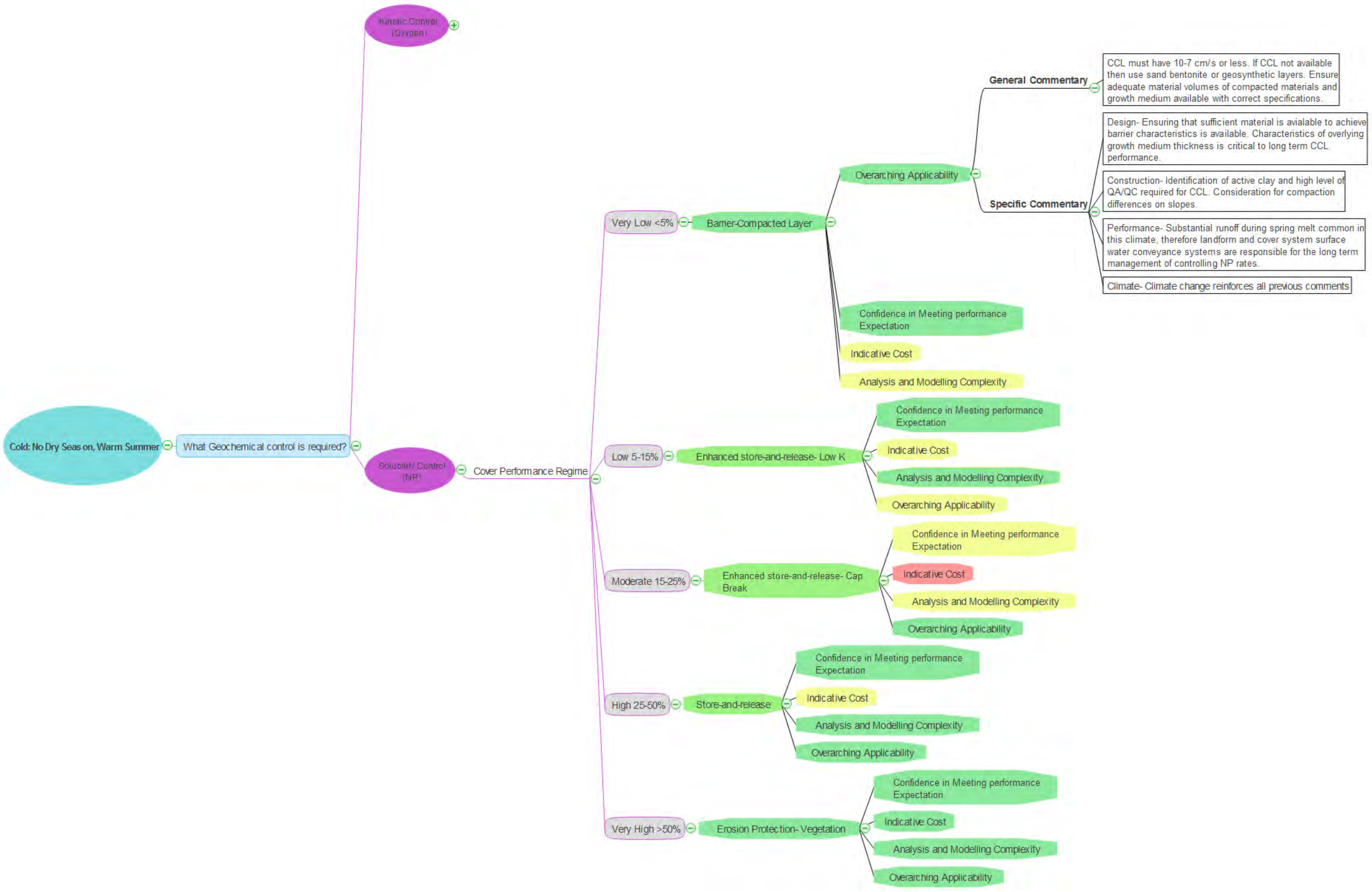
Design- Key issue is drainage of compacted layer leading to desaturation. Material that is as above in regards to material characteristics but thinner: 25-30cm OR placed in two lifts with less compaction control (see above). Keeping in mind that the issue is about drainage of the layer rather than evaporation from the surface. Growth medium is the same as above. Thinner growth medium will mean greater propensity in the summer to draw water from compacted layer and lower saturation and lead to higher oxygen ingress and increased likelihood of clay cracking.

Construction- High level of QA/QC on CCL construction and consideration for differences in compaction specs on sloping surfaces. Ensure no segregation occurs in overlying growth medium materials which could lead to preferential flow. Growth Medium thickness specification also important to ensure desiccation of the barrier layer does not occur. Winter construction considerations are important to consider. The construction season is significantly shorter than in other climates.

Performance- Freeze/thaw cycling can lead to loss of moisture retention capability

Climate- Climate change will tend to increase precipitation and therefore ability to maintain higher saturations, this will only serve to renforce performance.

1.2 Cold: No Dry Season, Warm Summer (NP)



CCL must have 10-7 cm/s or less. If CCL not available then use sand bentonite or geosynthetic layers. Ensure adequate material volumes of compacted materials and growth medium available with correct specifications.

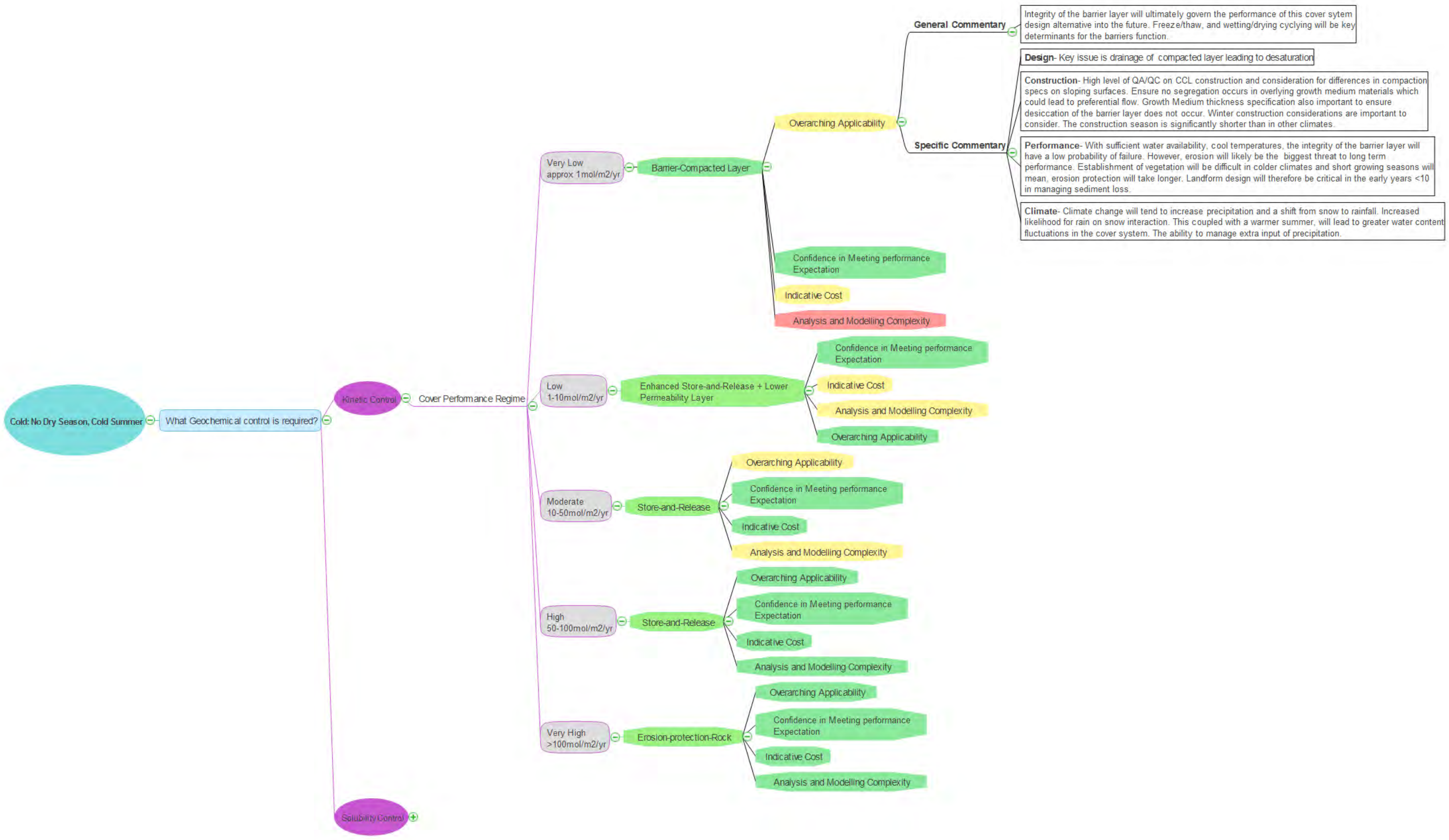
Design- Ensuring that sufficient material is avialable to achieve barrier characteristics is available. Characteristics of overlying growth medium thickness is critical to long term CCL performance.

Construction- Identification of active clay and high level of QA/QC required for CCL. Consideration for compaction differences on slopes.

Performance- Substantial runoff during spring melt common in this climate, therefore landform and cover system surface water conveyance systems are responsible for the long term management of controlling NP rates.

Climate- Climate change reinforces all previous comments

1.3 Cold: No Dry Season, Cold Summer (O_2)



Integrity of the barrier layer will ultimately govern the performance of this cover sytem design alternative into the future. Freeze/thaw, and wetting/drying cyclying will be key determinants for the barriers function.

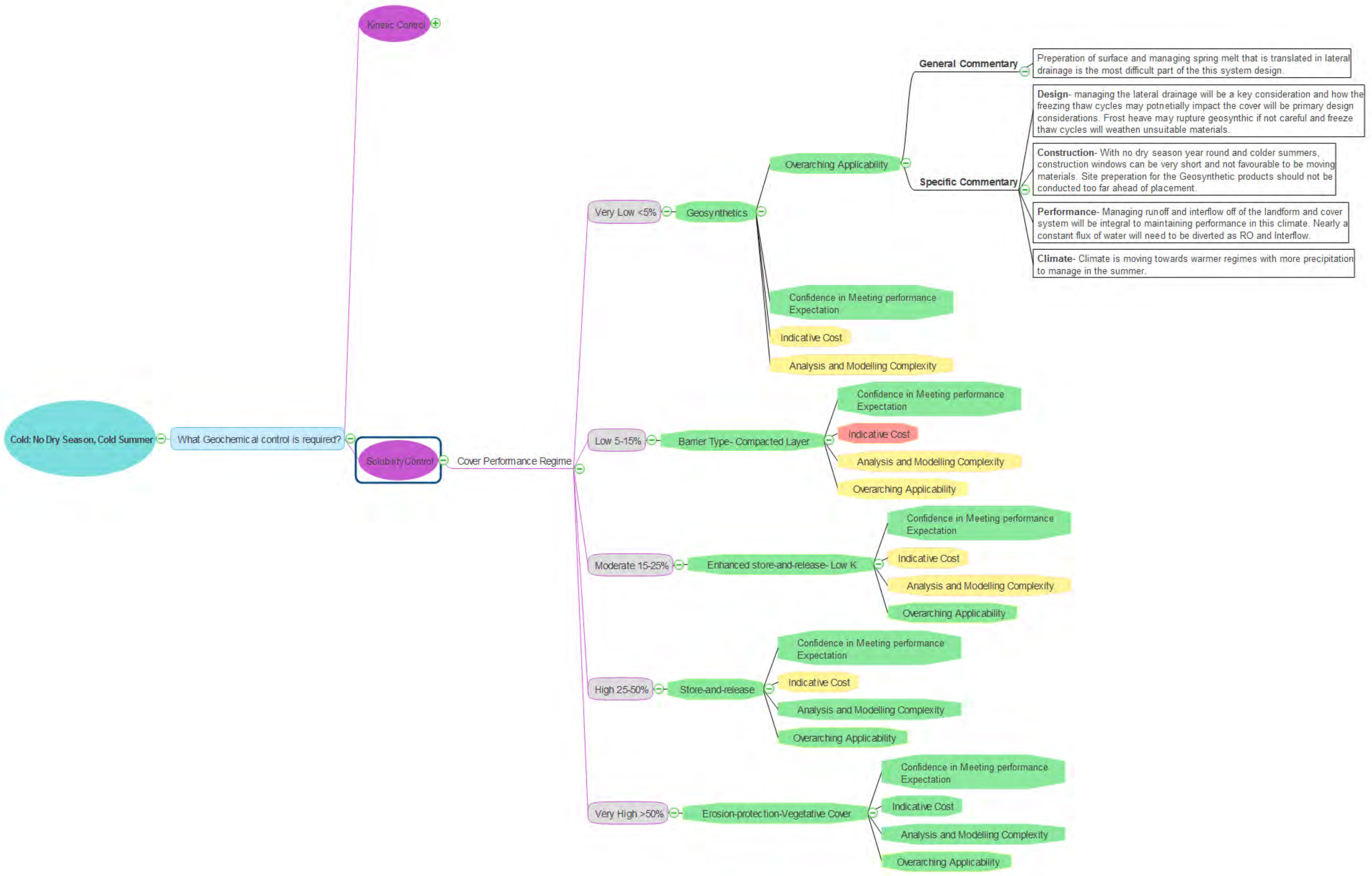
Design- Key issue is drainage of compacted layer leading to desaturation

Construction- High level of QA/QC on CCL construction and consideration for differences in compaction specs on sloping surfaces. Ensure no segregation occurs in overlying growth medium materials which could lead to preferential flow. Growth Medium thickness specification also important to ensure desiccation of the barrier layer does not occur. Winter construction considerations are important to consider. The construction season is significantly shorter than in other climates.

Performance- With sufficient water availability, cool temperatures, the integrity of the barrier layer will have a low probability of failure. However, erosion will likely be the biggest threat to long term performance. Establishment of vegetation will be difficult in colder climates and short growing seasons will mean, erosion protection will take longer. Landform design will therefore be critical in the early years <10 in managing sediment loss.

Climate- Climate change will tend to increase precipitation and a shift from snow to rainfall. Increased likelihood for rain on snow interaction. This coupled with a warmer summer, will lead to greater water content fluctuations in the cover system. The ability to manage extra input of precipitation.

1.4 Cold: No Dry Season, Cold Summer (NP)



General Commentary

Preperation of surface and managing spring melt that is translated in lateral drainage is the most difficult part of the this system design.

Specific Commentary

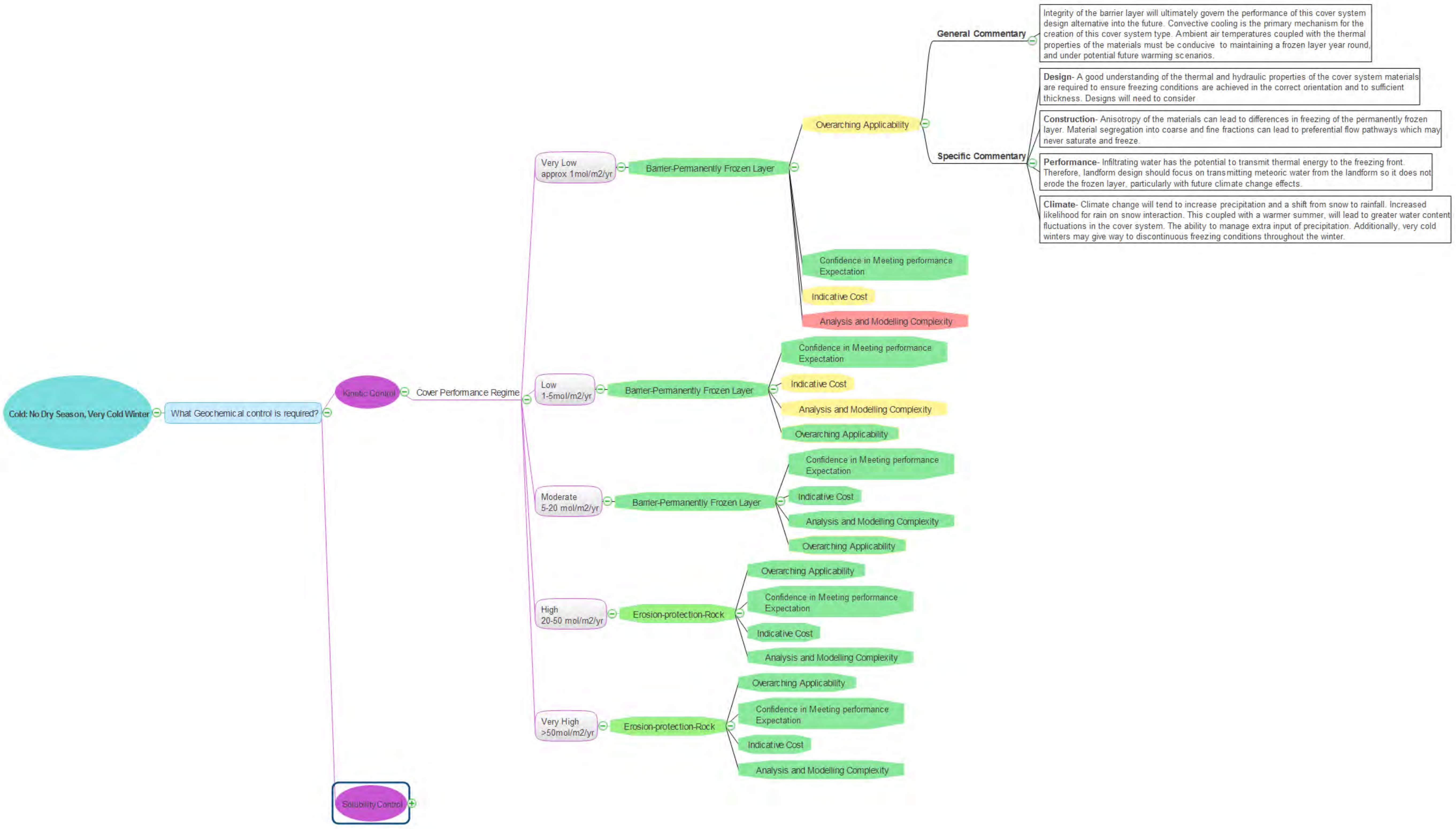
Design- managing the lateral drainage will be a key consideration and how the freezing thaw cycles may potnetially impact the cover will be primary design considerations. Frost heave may rupture geosynthic if not careful and freeze thaw cycles will weathen unsuitable materials.

Construction- With no dry season year round and colder summers, construction windows can be very short and not favourable to be moving materials. Site preperation for the Geosynthetic products should not be conducted too far ahead of placement.

Performance- Managing runoff and interflow off of the landform and cover system will be integral to maintaining performance in this climate. Nearly a constant flux of water will need to be diverted as RO and Interflow.

Climate- Climate is moving towards warmer regimes with more precipitation to manage in the summer.

1.5 Cold: No Dry Season, Very Cold Winter (O_2)



Integrity of the barrier layer will ultimately govern the performance of this cover system design alternative into the future. Convective cooling is the primary mechanism for the creation of this cover system type. Ambient air temperatures coupled with the thermal properties of the materials must be conducive to maintaining a frozen layer year round, and under potential future warming scenarios.

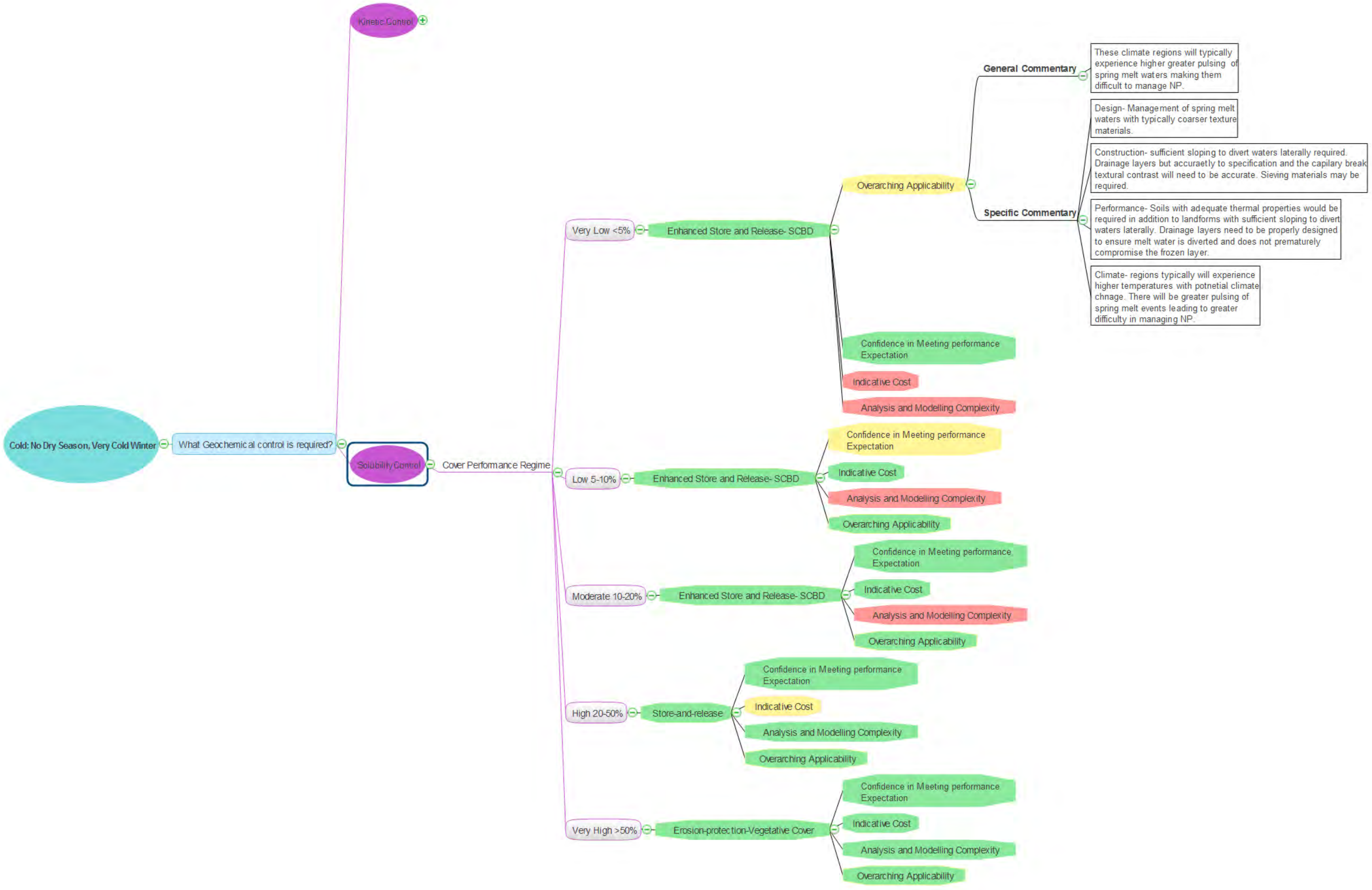
Design- A good understanding of the thermal and hydraulic properties of the cover system materials are required to ensure freezing conditions are achieved in the correct orientation and to sufficient thickness. Designs will need to consider

Construction- Anisotropy of the materials can lead to differences in freezing of the permanently frozen layer. Material segregation into coarse and fine fractions can lead to preferential flow pathways which may never saturate and freeze.

Performance- Infiltrating water has the potential to transmit thermal energy to the freezing front. Therefore, landform design should focus on transmitting meteoric water from the landform so it does not erode the frozen layer, particularly with future climate change effects.

Climate- Climate change will tend to increase precipitation and a shift from snow to rainfall. Increased likelihood for rain on snow interaction. This coupled with a warmer summer, will lead to greater water content fluctuations in the cover system. The ability to manage extra input of precipitation. Additionally, very cold winters may give way to discontinuous freezing conditions throughout the winter.

1.6 Cold: No Dry Season, Very Cold Winter (NP)



These climate regions will typically experience higher greater pulsing of spring melt waters making them difficult to manage NP.

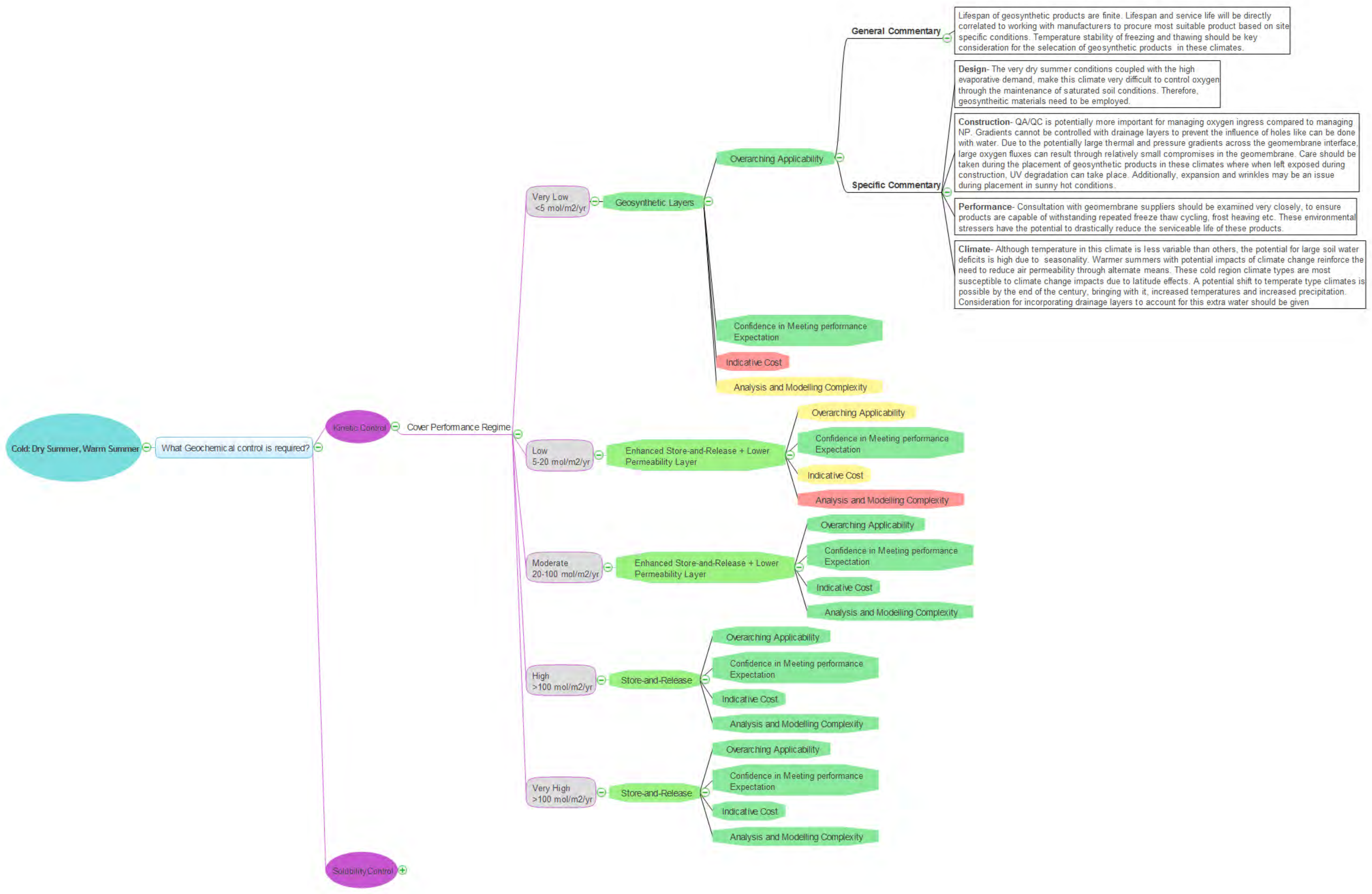
Design- Management of spring melt waters with typically coarser texture materials.

Construction- sufficient sloping to divert waters laterally required. Drainage layers but accuraetly to specification and the capilary break textural contrast will need to be accurate. Sieving materials may be required.

Performance- Soils with adequate thermal properties would be required in addition to landforms with sufficient sloping to divert waters laterally. Drainage layers need to be properly designed to ensure melt water is diverted and does not prematurely compromise the frozen layer.

Climate- regions typically will experience higher temperatures with potnetial climate chnage. There will be greater pulsing of spring melt events leading to greater difficulty in managing NP.

1.7 Cold: Dry Summer, Warm Summer (O_2)



Lifespan of geosynthetic products are finite. Lifespan and service life will be directly correlated to working with manufacturers to procure most suitable product based on site specific conditions. Temperature stability of freezing and thawing should be key consideration for the selecation of geosynthetic products in these climates.

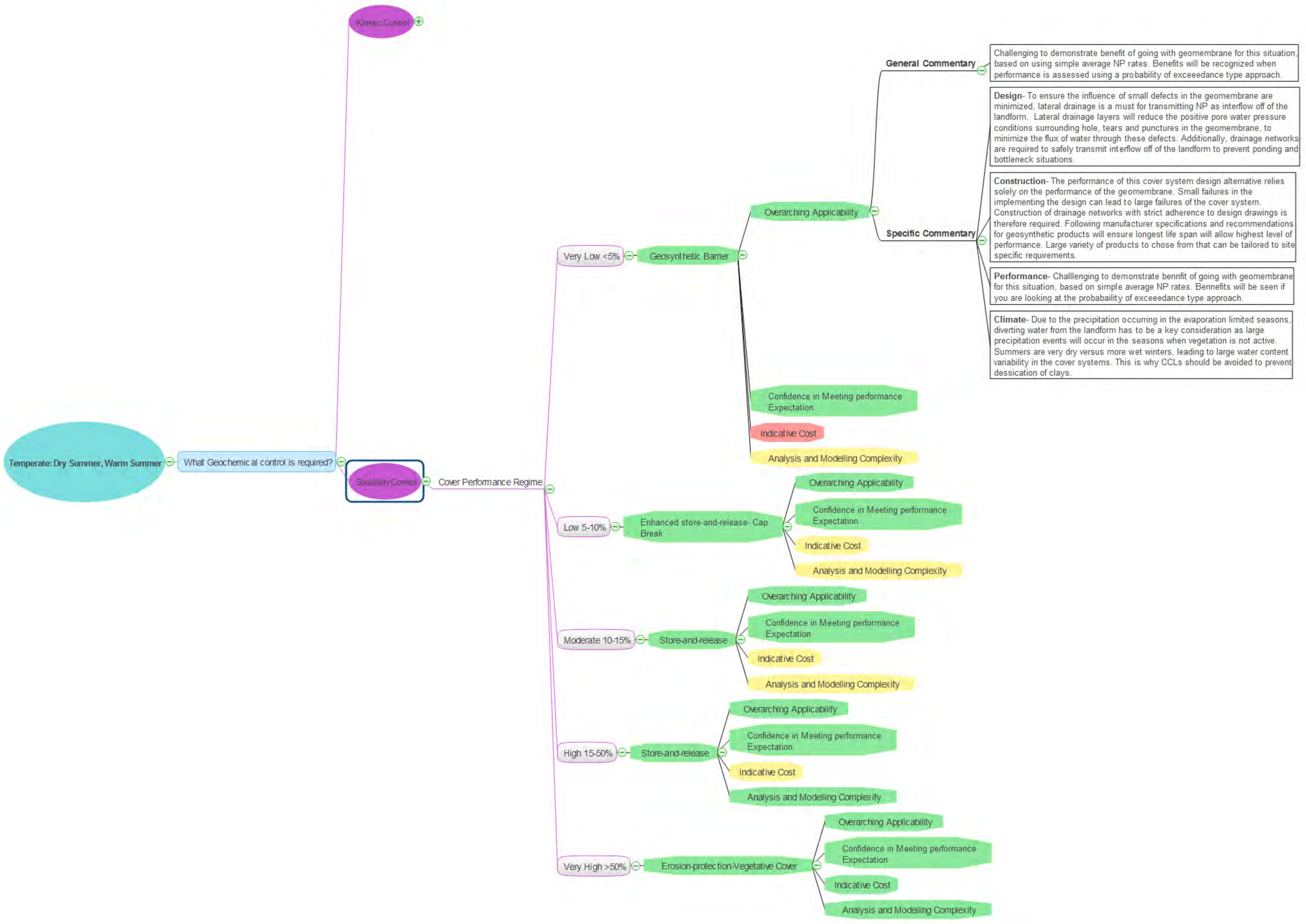
Design- The very dry summer conditions coupled with the high evaporative demand, make this climate very difficult to control oxygen through the maintenance of saturated soil conditions. Therefore, geosyntheitic materials need to be employed.

Construction- QA/QC is potentially more important for managing oxygen ingress compared to managing NP. Gradients cannot be controlled with drainage layers to prevent the influence of holes like can be done with water. Due to the potentially large thermal and pressure gradients across the geomembrane interface, large oxygen fluxes can result through relatively small compromises in the geomembrane. Care should be taken during the placement of geosynthetic products in these climates where when left exposed during construction, UV degradation can take place. Additionally, expansion and wrinkles may be an issue during placement in sunny hot conditions.

Performance- Consultation with geomembrane suppliers should be examined very closely, to ensure products are capable of withstanding repeated freeze thaw cycling, frost heaving etc. These environmental stressers have the potential to drastically reduce the serviceable life of these products.

Climate- Although temperature in this climate is less variable than others, the potential for large soil water deficits is high due to seasonality. Warmer summers with potential impacts of climate change reinforce the need to reduce air permeability through alternate means. These cold region climate types are most susceptible to climate change impacts due to latitude effects. A potential shift to temperate type climates is possible by the end of the century, bringing with it, increased temperatures and increased precipitation. Consideration for incorporating drainage layers to account for this extra water should be given

1.8 Cold: Dry Summer, Warm Summer (NP)



Challenging to demonstrate benefit of going with geomembrane for this situation, based on using simple average NP rates. Benefits will be recognized when performance is assessed using a probability of exceeedance type approach.

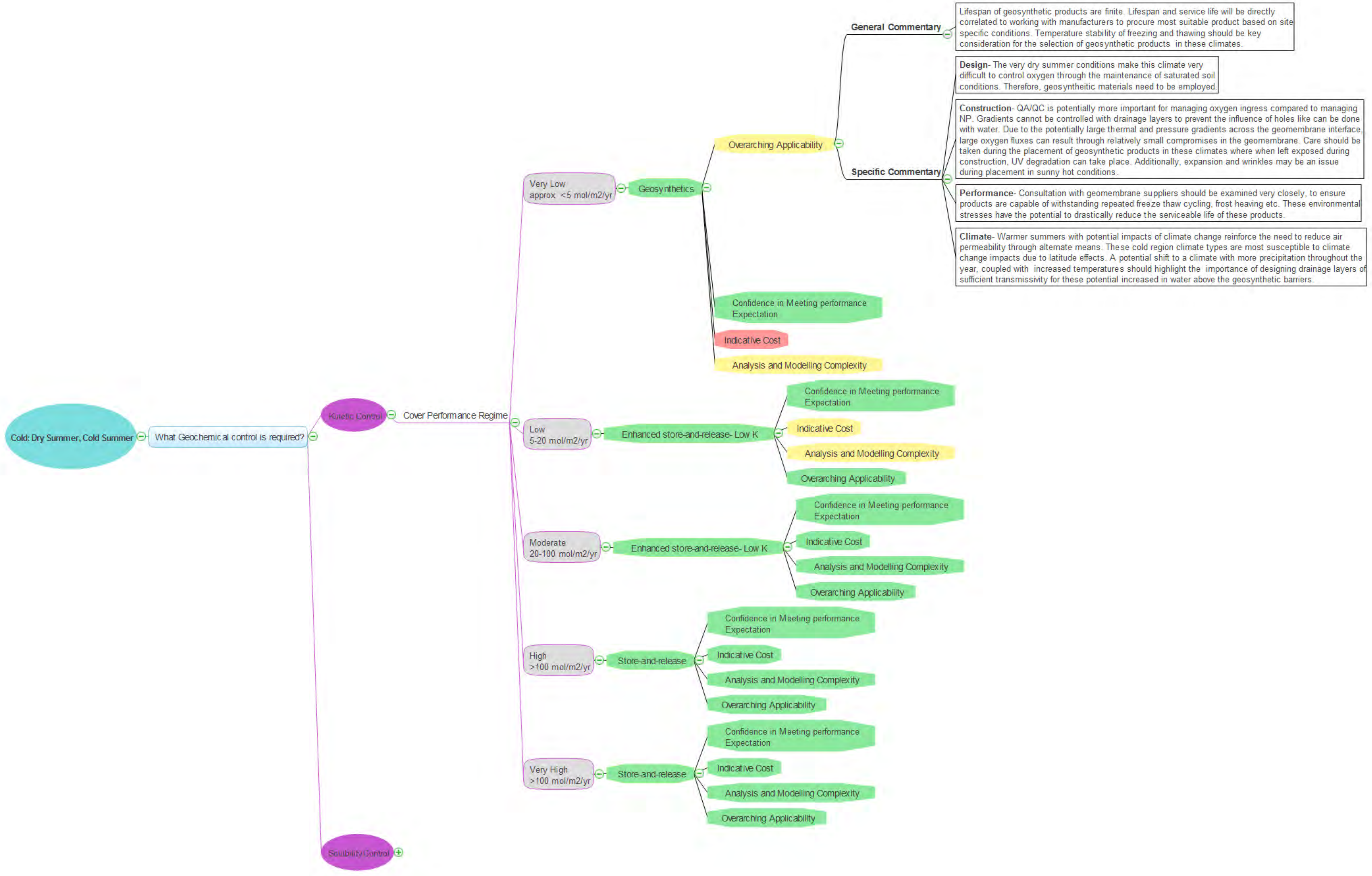
Design- To ensure the influence of small defects in the geomembrane are minimized, lateral drainage is a must for transmitting NP as interflow off of the landform. Lateral drainage layers will reduce the positive pore water pressure conditions surrounding hole, tears and punctures in the geomembrane, to minimize the flux of water through these defects. Additionally, drainage networks are required to safely transmit interflow off of the landform to prevent ponding and bottleneck situations.

Construction- The performance of this cover system design alternative relies solely on the performance of the geomembrane. Small failures in the implementing the design can lead to large failures of the cover system. Construction of drainage networks with strict adherence to design drawings is therefore required. Following manufacturer specifications and recommendations for geosynthetic products will ensure longest life span will allow highest level of performance. Large variety of products to chose from that can be tailored to site specific requirements.

Performance- Challlenging to demonstrate bennfit of going with geomembrane for this situation, based on simple average NP rates. Bennefits will be seen if you are looking at the probabaility of exceeedance type approach.

Climate- Due to the precipitation occurring in the evaporation limited seasons, diverting water from the landform has to be a key consideration as large precipitation events will occur in the seasons when vegetation is not active. Summers are very dry versus more wet winters, leading to large water content variability in the cover systems. This is why CCLs should be avoided to prevent dessication of clays.

1.9 Cold: Dry Summer, Cold Summer (O_2)



Lifespan of geosynthetic products are finite. Lifespan and service life will be directly correlated to working with manufacturers to procure most suitable product based on site specific conditions. Temperature stability of freezing and thawing should be key consideration for the selection of geosynthetic products in these climates.

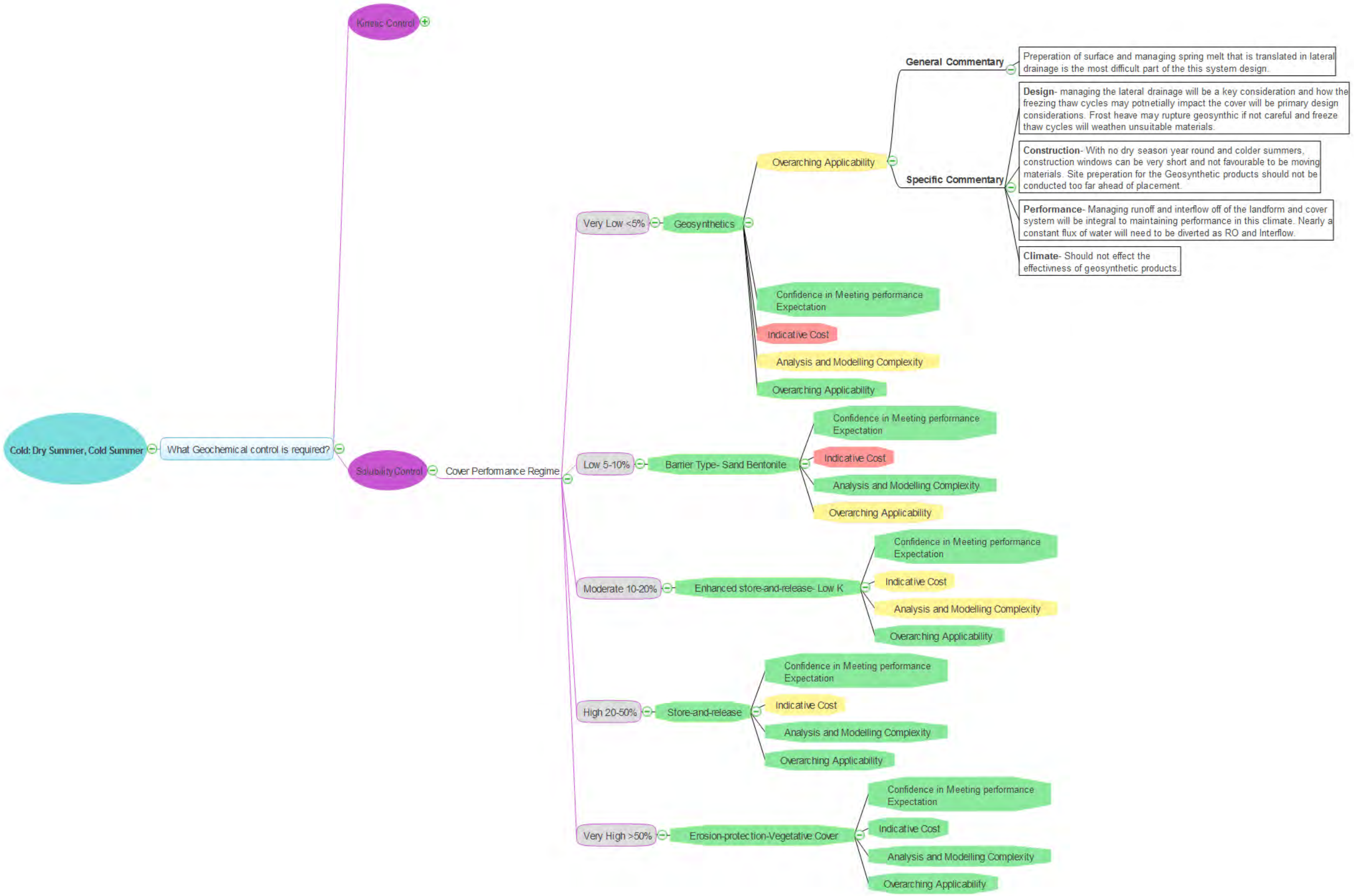
Design- The very dry summer conditions make this climate very difficult to control oxygen through the maintenance of saturated soil conditions. Therefore, geosyntheitic materials need to be employed.

Construction- QA/QC is potentially more important for managing oxygen ingress compared to managing NP. Gradients cannot be controlled with drainage layers to prevent the influence of holes like can be done with water. Due to the potentially large thermal and pressure gradients across the geomembrane interface, large oxygen fluxes can result through relatively small compromises in the geomembrane. Care should be taken during the placement of geosynthetic products in these climates where when left exposed during construction, UV degradation can take place. Additionally, expansion and wrinkles may be an issue during placement in sunny hot conditions.

Performance- Consultation with geomembrane suppliers should be examined very closely, to ensure products are capable of withstanding repeated freeze thaw cycling, frost heaving etc. These environmental stresses have the potential to drastically reduce the serviceable life of these products.

Climate- Warmer summers with potential impacts of climate change reinforce the need to reduce air permeability through alternate means. These cold region climate types are most susceptible to climate change impacts due to latitude effects. A potential shift to a climate with more precipitation throughout the year, coupled with increased temperatures should highlight the importance of designing drainage layers of sufficient transmissivity for these potential increased in water above the geosynthetic barriers.

1.10 Cold: Dry Summer, Cold Summer (NP)



Preperation of surface and managing spring melt that is translated in lateral drainage is the most difficult part of the this system design.

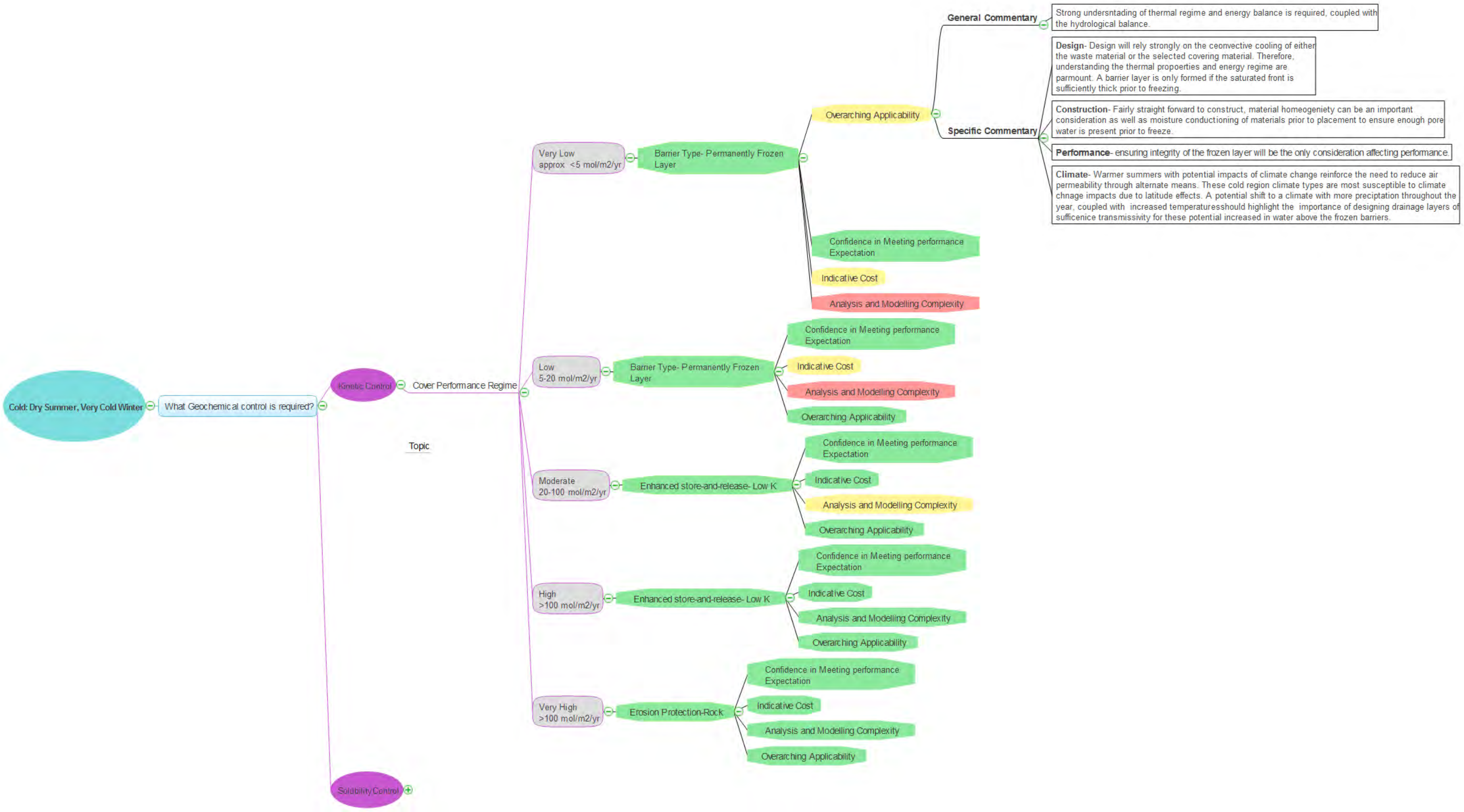
Design- managing the lateral drainage will be a key consideration and how the freezing thaw cycles may potnetially impact the cover will be primary design considerations. Frost heave may rupture geosynthic if not careful and freeze thaw cycles will weathen unsuitable materials.

Construction- With no dry season year round and colder summers, construction windows can be very short and not favourable to be moving materials. Site preperation for the Geosynthetic products should not be conducted too far ahead of placement.

Performance- Managing runoff and interflow off of the landform and cover system will be integral to maintaining performance in this climate. Nearly a constant flux of water will need to be diverted as RO and Interflow.

Climate- Should not effect the effectivness of geosynthetic products.

1.11 Cold: Dry Summer, Very Cold Winter (O_2)



Strong undersntading of thermal regime and energy balance is required, coupled with the hydrological balance.

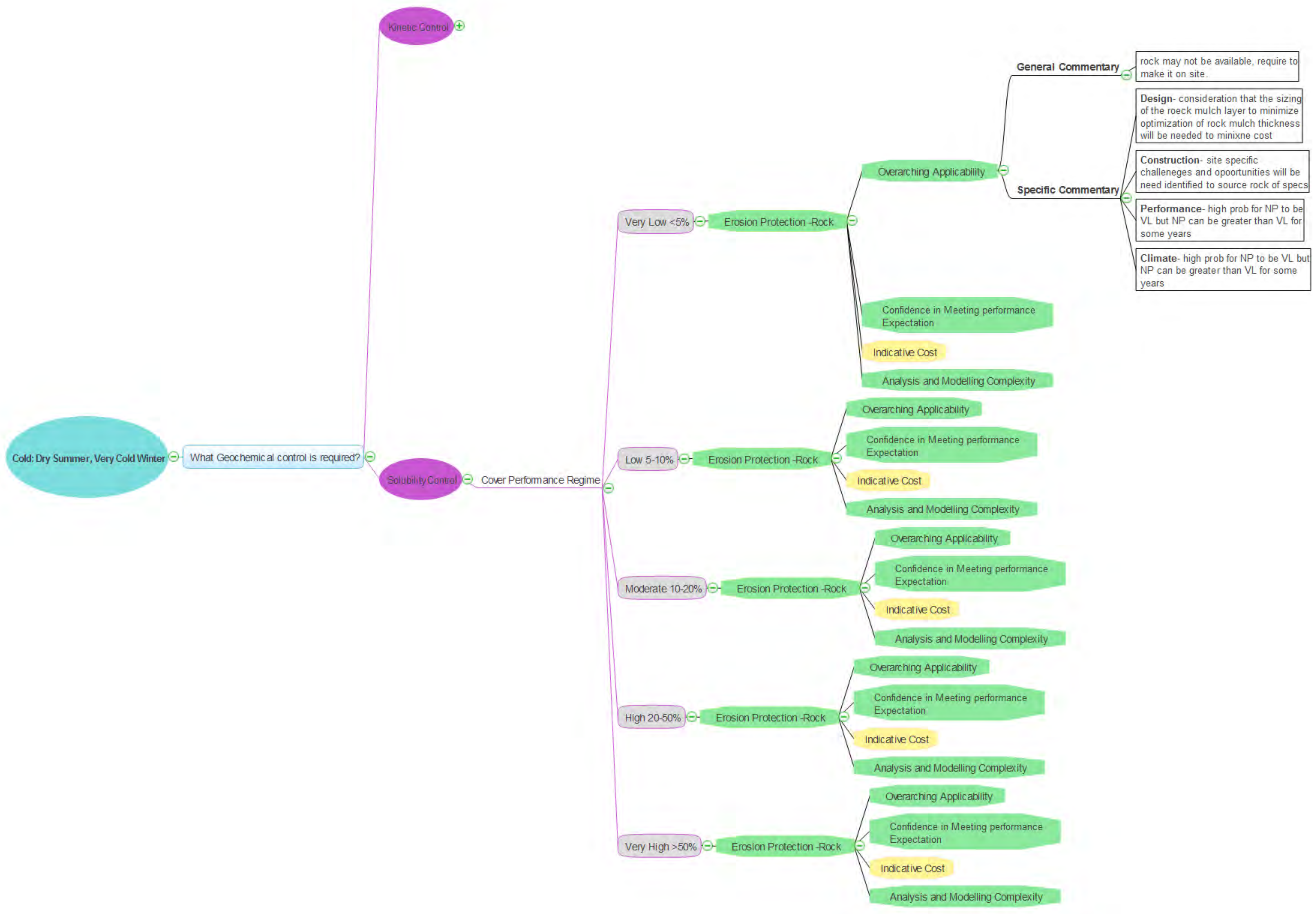
Design- Design will rely strongly on the ceonvective cooling of either the waste material or the selected covering material. Therefore, understanding the thermal propoerties and energy regime are parmount. A barrier layer is only formed if the saturated front is sufficiently thick prior to freezing.

Construction- Fairly straight forward to construct, material homeogeniety can be an important consideration as well as moisture conductioning of materials prior to placement to ensure enough pore water is present prior to freeze.

Performance- ensuring integrity of the frozen layer will be the only consideration affecting performance.

Climate- Warmer summers with potential impacts of climate change reinforce the need to reduce air permeability through alternate means. These cold region climate types are most susceptible to climate chnage impacts due to latitude effects. A potential shift to a climate with more preciptation throughout the year, coupled with increased temperaturesshould highlight the importance of designing drainage layers of sufficenice transmissivity for these potential increased in water above the frozen barriers.

1.12 Cold: Dry Summer, Very Cold Winter (NP)



rock may not be available, require to make it on site.

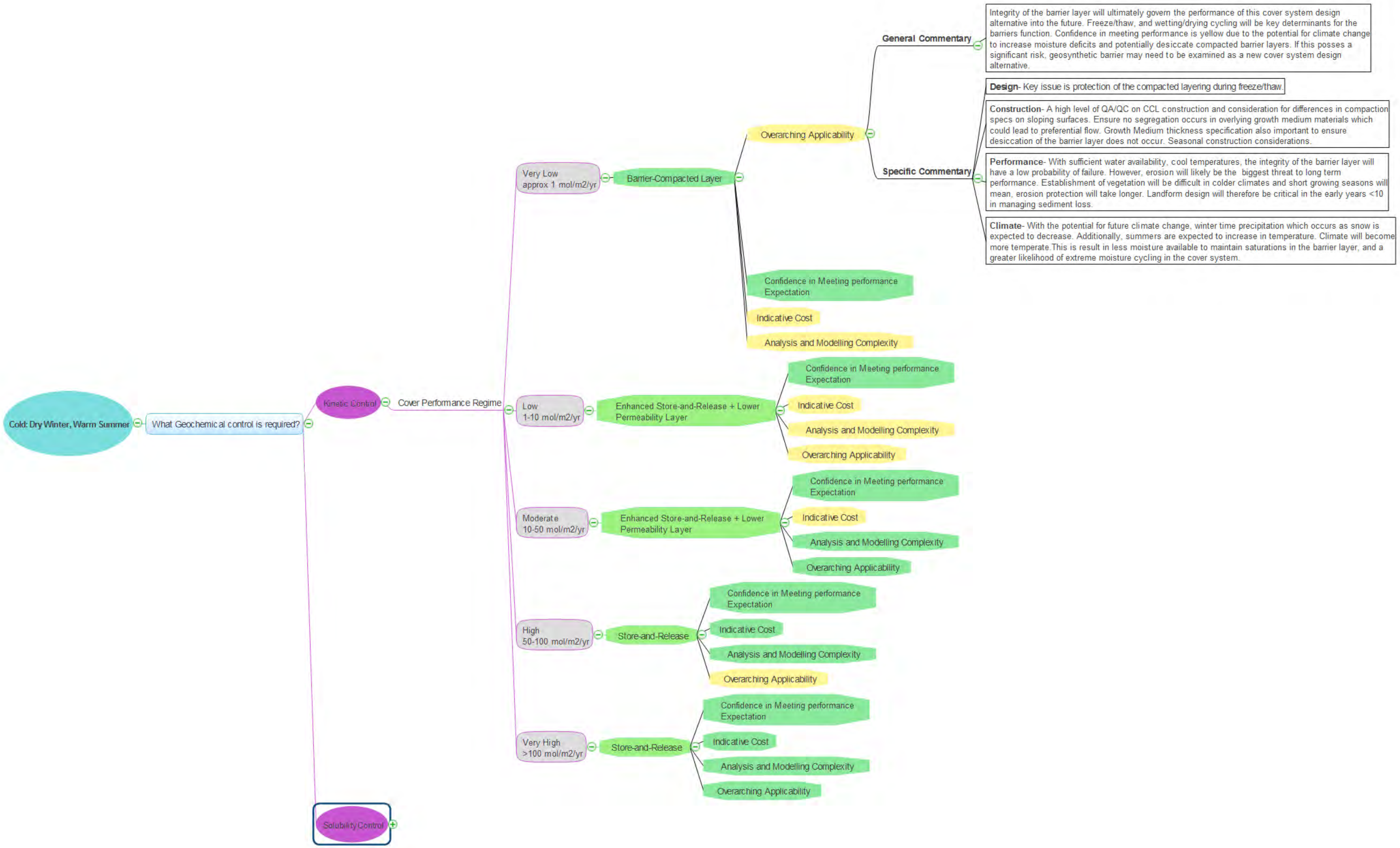
Design- consideration that the sizing of the roeck mulch layer to minimize optimization of rock mulch thickness will be needed to minixne cost

Construction- site specific challeneges and opoortunities will be need identified to source rock of specs

Performance- high prob for NP to be VL but NP can be greater than VL for some years

Climate- high prob for NP to be VL but NP can be greater than VL for some years

1.13 Cold: Dry Winter, Warm Summer (O_2)



Integrity of the barrier layer will ultimately govern the performance of this cover system design alternative into the future. Freeze/thaw, and wetting/drying cycling will be key determinants for the barriers function. Confidence in meeting performance is yellow due to the potential for climate change to increase moisture deficits and potentially desiccate compacted barrier layers. If this posses a significant risk, geosynthetic barrier may need to be examined as a new cover system design alternative.

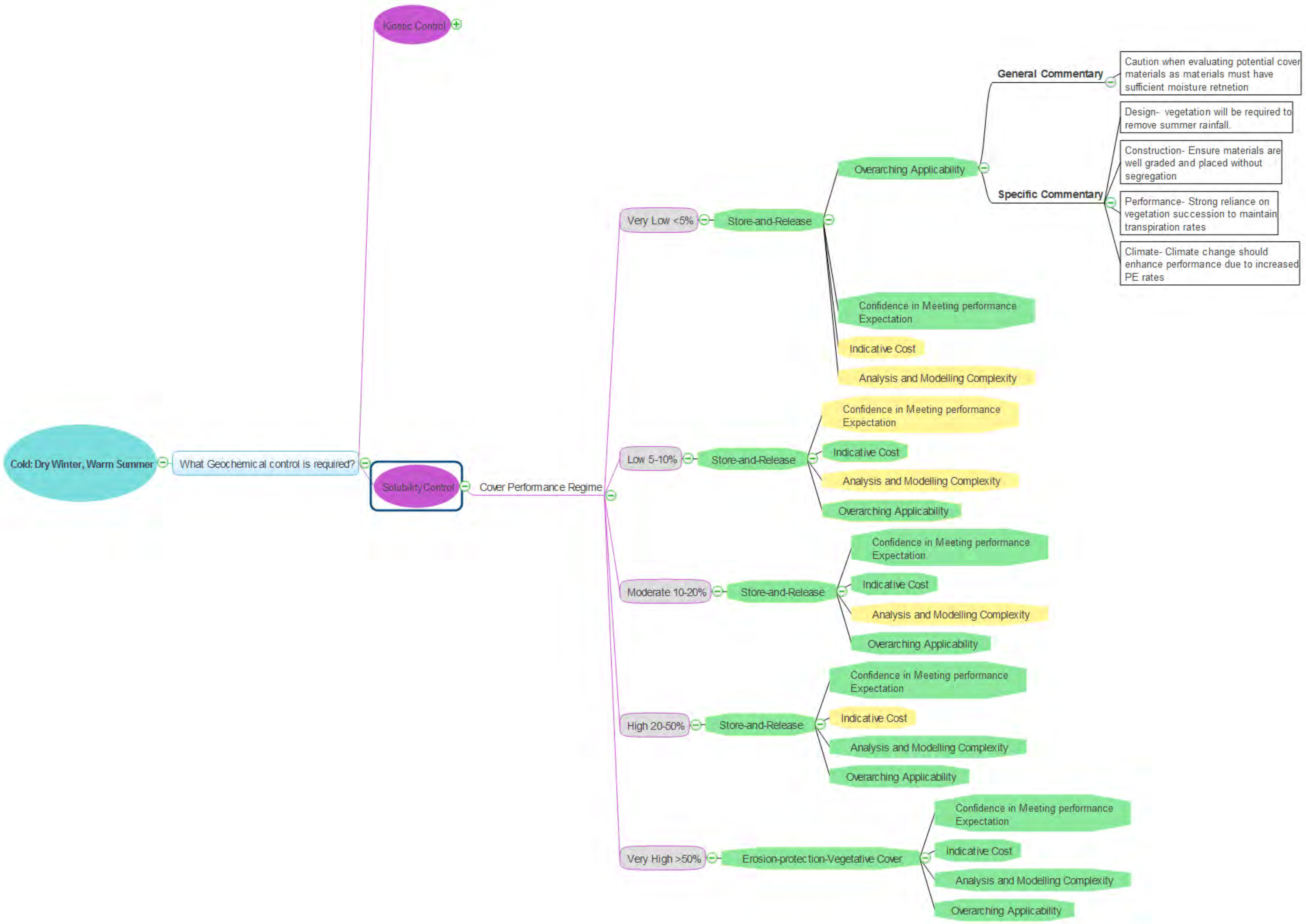
Design- Key issue is protection of the compacted layering during freeze/thaw.

Construction- A high level of QA/QC on CCL construction and consideration for differences in compaction specs on sloping surfaces. Ensure no segregation occurs in overlying growth medium materials which could lead to preferential flow. Growth Medium thickness specification also important to ensure desiccation of the barrier layer does not occur. Seasonal construction considerations.

Performance- With sufficient water availability, cool temperatures, the integrity of the barrier layer will have a low probability of failure. However, erosion will likely be the biggest threat to long term performance. Establishment of vegetation will be difficult in colder climates and short growing seasons will mean, erosion protection will take longer. Landform design will therefore be critical in the early years <10 in managing sediment loss.

Climate- With the potential for future climate change, winter time precipitation which occurs as snow is expected to decrease. Additionally, summers are expected to increase in temperature. Climate will become more temperate.This is result in less moisture available to maintain saturations in the barrier layer, and a greater likelihood of extreme moisture cycling in the cover system.

1.14 Cold: Dry Winter, Warm Summer (NP)



Caution when evaluating potential cover materials as materials must have sufficient moisture retnetion

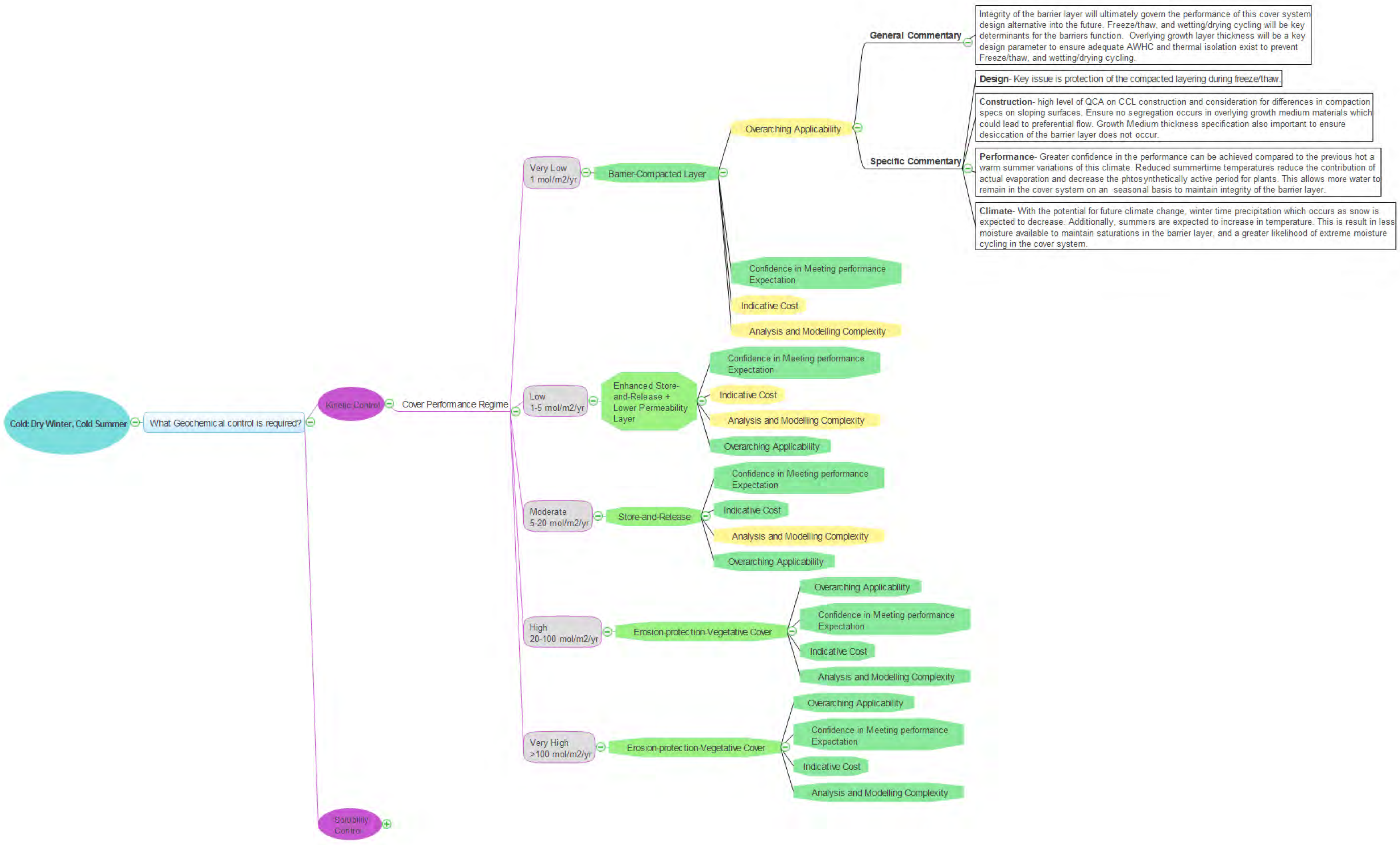
Design- vegetation will be required to remove summer rainfall.

Construction- Ensure materials are well graded and placed without segregation

Performance- Strong reliance on vegetation succession to maintain transpiration rates

Climate- Climate change should enhance performance due to increased PE rates

1.15 Cold: Dry Winter, Cold Summer (O_2)



Integrity of the barrier layer will ultimately govern the performance of this cover system design alternative into the future. Freeze/thaw, and wetting/drying cycling will be key determinants for the barriers function. Overlying growth layer thickness will be a key design parameter to ensure adequate AWHC and thermal isolation exist to prevent Freeze/thaw, and wetting/drying cycling.

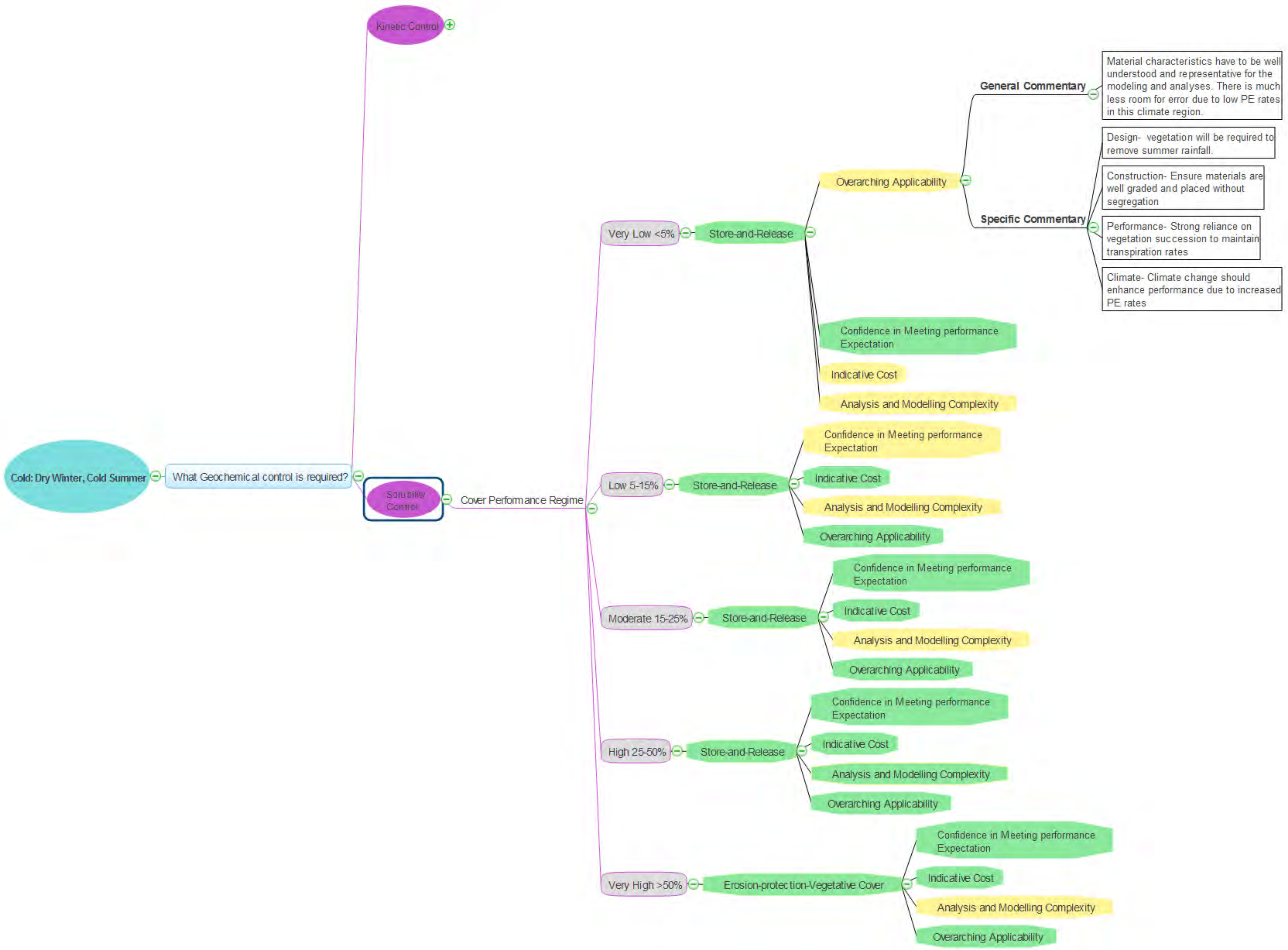
Design- Key issue is protection of the compacted layering during freeze/thaw.

Construction- high level of QCA on CCL construction and consideration for differences in compaction specs on sloping surfaces. Ensure no segregation occurs in overlying growth medium materials which could lead to preferential flow. Growth Medium thickness specification also important to ensure desiccation of the barrier layer does not occur.

Performance- Greater confidence in the performance can be achieved compared to the previous hot a warm summer variations of this climate. Reduced summertime temperatures reduce the contribution of actual evaporation and decrease the phtosynthetically active period for plants. This allows more water to remain in the cover system on an seasonal basis to maintain integrity of the barrier layer.

Climate- With the potential for future climate change, winter time precipitation which occurs as snow is expected to decrease. Additionally, summers are expected to increase in temperature. This is result in less moisture available to maintain saturations in the barrier layer, and a greater likelihood of extreme moisture cycling in the cover system.

1.16 Cold: Dry Winter, Cold Summer (NP)



General Commentary

Material characteristics have to be well understood and representative for the modeling and analyses. There is much less room for error due to low PE rates in this climate region.

Specific Commentary

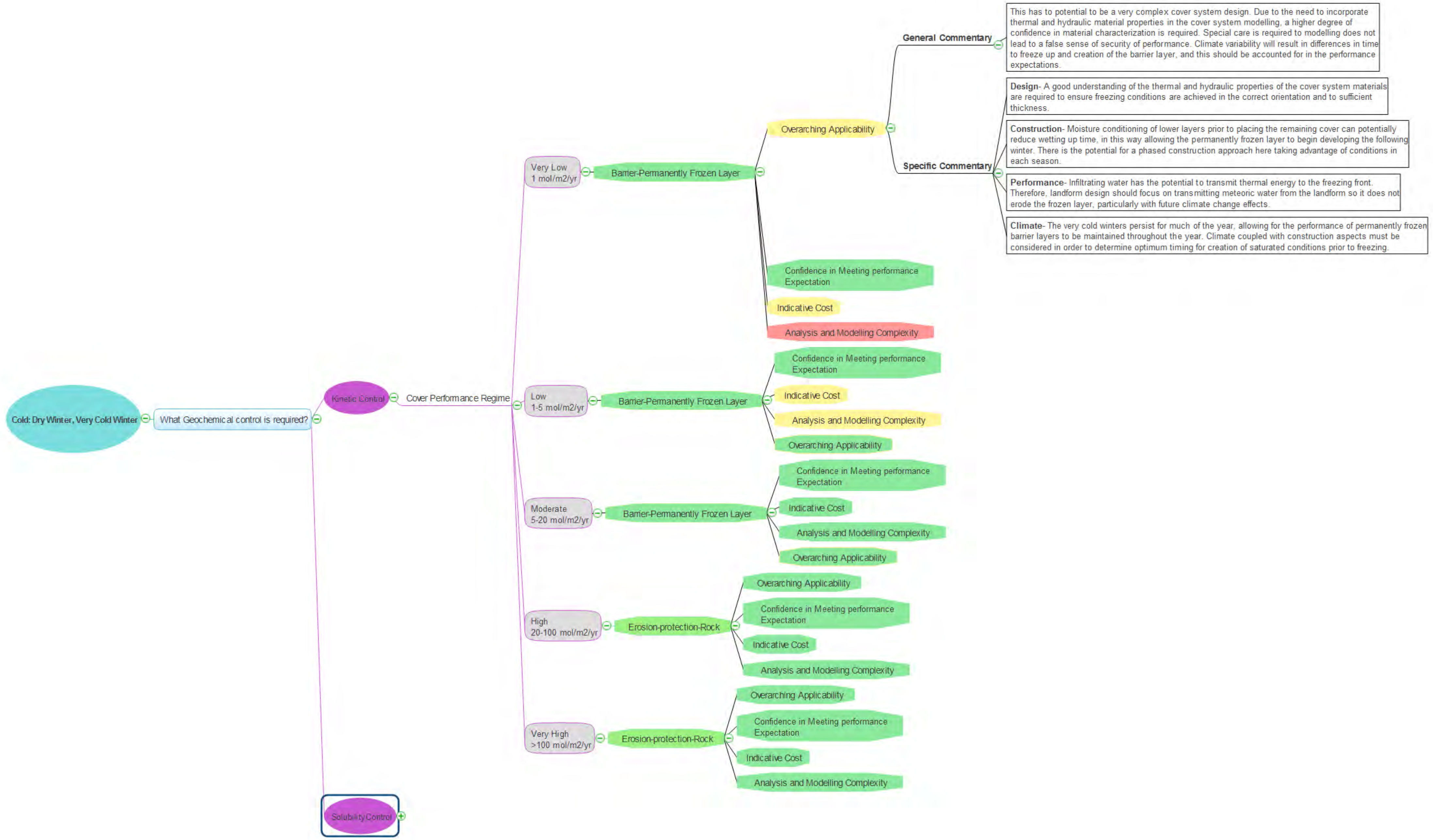
Design- vegetation will be required to remove summer rainfall.

Construction- Ensure materials are well graded and placed without segregation

Performance- Strong reliance on vegetation succession to maintain transpiration rates

Climate- Climate change should enhance performance due to increased PE rates

1.17 Cold: Dry Winter, Very Cold Winter (O_2)



This has to potential to be a very complex cover system design. Due to the need to incorporate thermal and hydraulic material properties in the cover system modelling, a higher degree of confidence in material characterization is required. Special care is required to modelling does not lead to a false sense of security of performance. Climate variability will result in differences in time to freeze up and creation of the barrier layer, and this should be accounted for in the performance expectations.

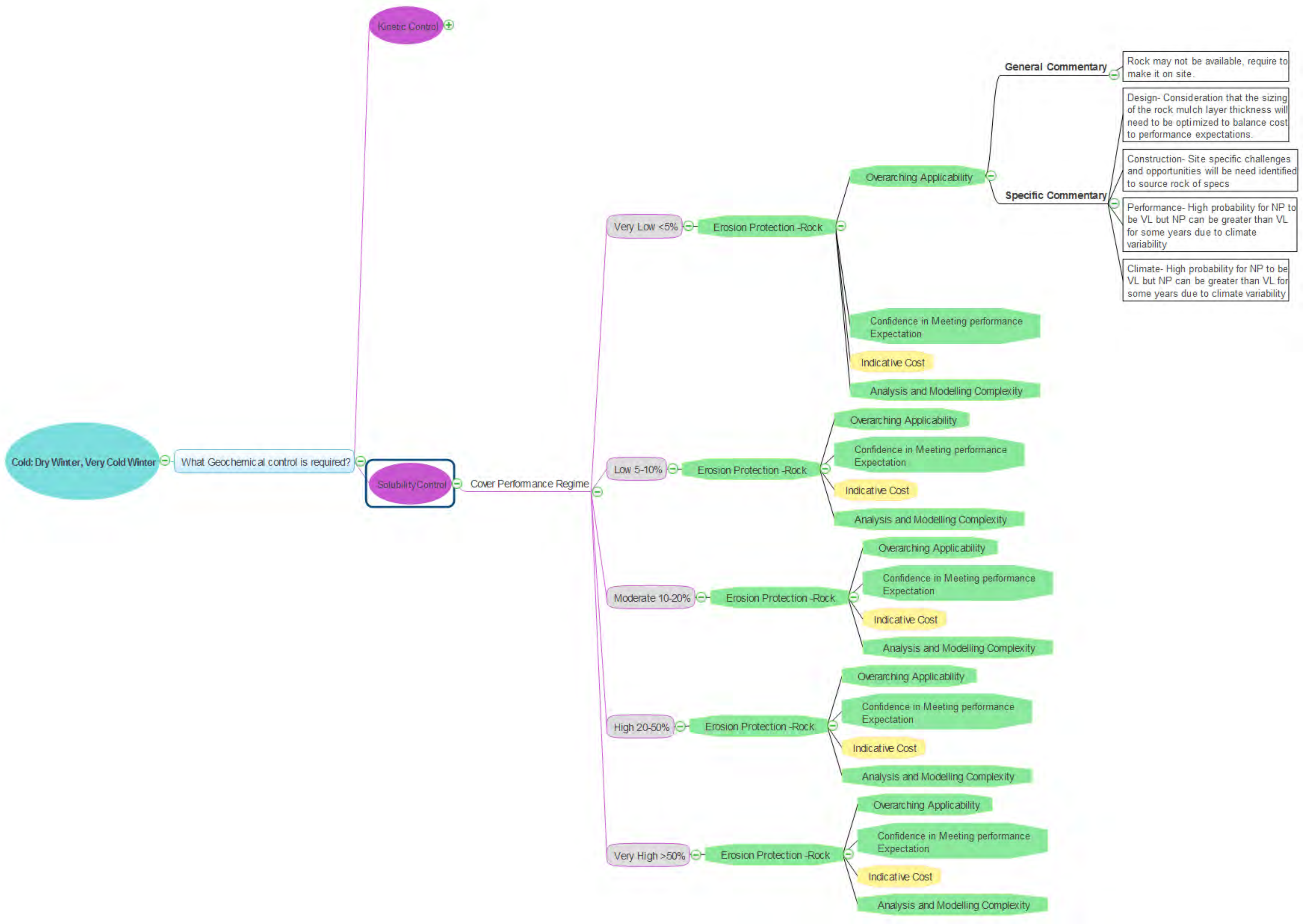
Design- A good understanding of the thermal and hydraulic properties of the cover system materials are required to ensure freezing conditions are achieved in the correct orientation and to sufficient thickness.

Construction- Moisture conditioning of lower layers prior to placing the remaining cover can potentially reduce wetting up time, in this way allowing the permanently frozen layer to begin developing the following winter. There is the potential for a phased construction approach here taking advantage of conditions in each season.

Performance- Infiltrating water has the potential to transmit thermal energy to the freezing front. Therefore, landform design should focus on transmitting meteoric water from the landform so it does not erode the frozen layer, particularly with future climate change effects.

Climate- The very cold winters persist for much of the year, allowing for the performance of permanently frozen barrier layers to be maintained throughout the year. Climate coupled with construction aspects must be considered in order to determine optimum timing for creation of saturated conditions prior to freezing.

1.18 Cold: Dry Winter, Very Cold Winter (NP)



Rock may not be available, require to make it on site.

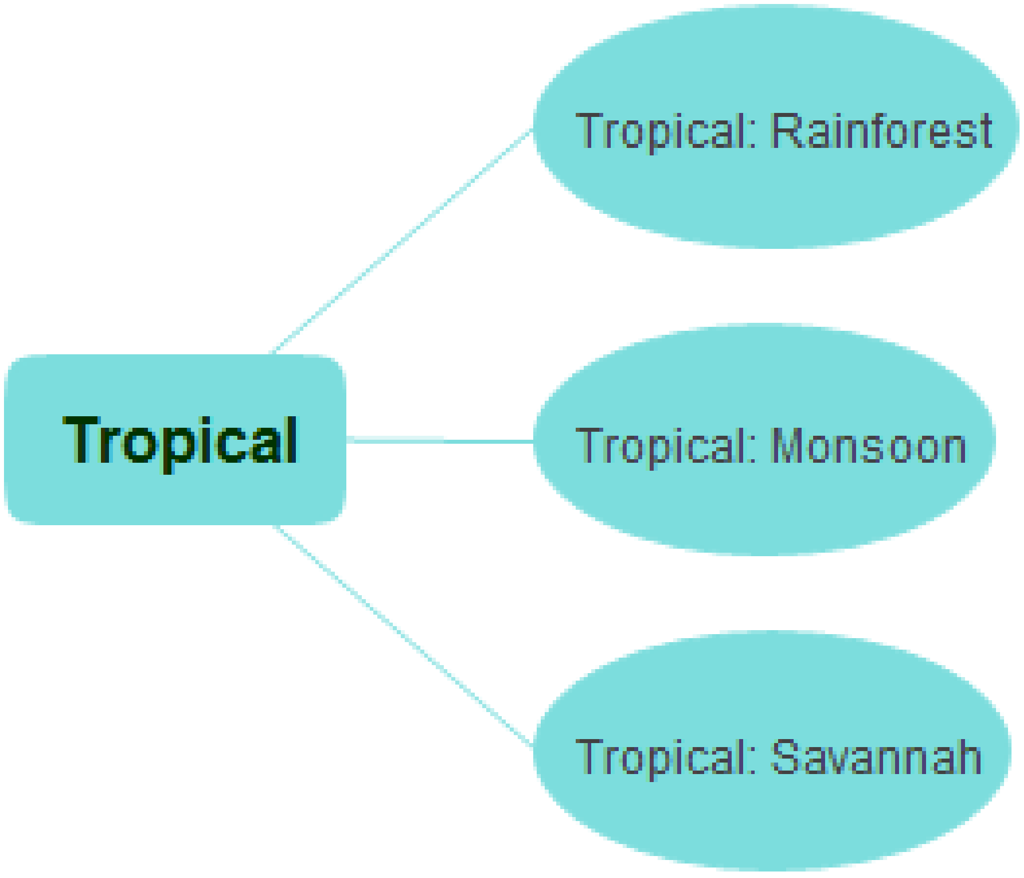
Design- Consideration that the sizing of the rock mulch layer thickness will need to be optimized to balance cost to performance expectations.

Construction- Site specific challenges and opportunities will be need identified to source rock of specs

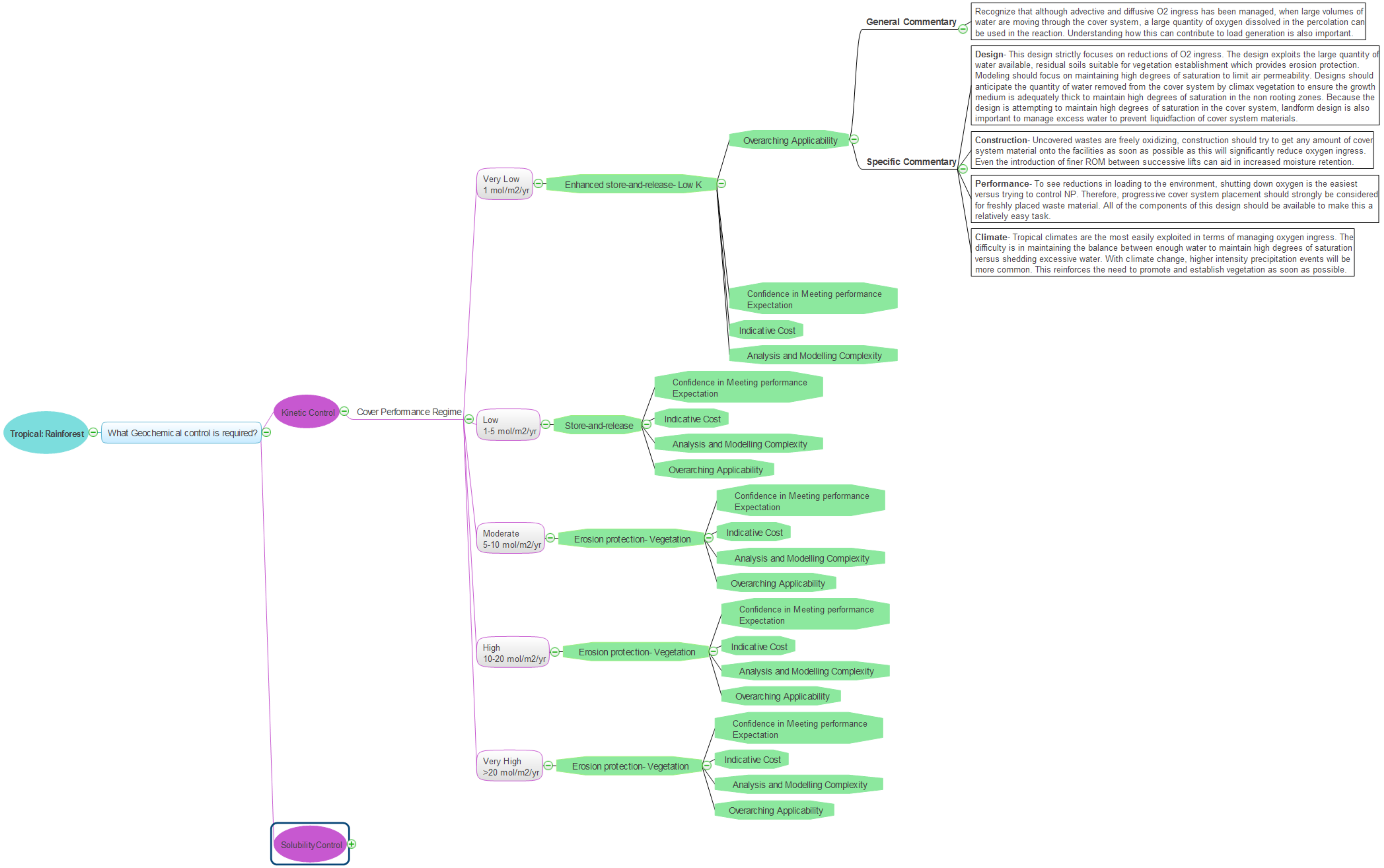
Performance- High probability for NP to be VL but NP can be greater than VL for some years due to climate variability

Climate- High probability for NP to be VL but NP can be greater than VL for some years due to climate variability

2 TROPICAL CLIMATE OVERVIEW



2.1 Tropical: Rainforest (O_2)



Recognize that although advective and diffusive O2 ingress has been managed, when large volumes of water are moving through the cover system, a large quantity of oxygen dissolved in the percolation can be used in the reaction. Understanding how this can contribute to load generation is also important.

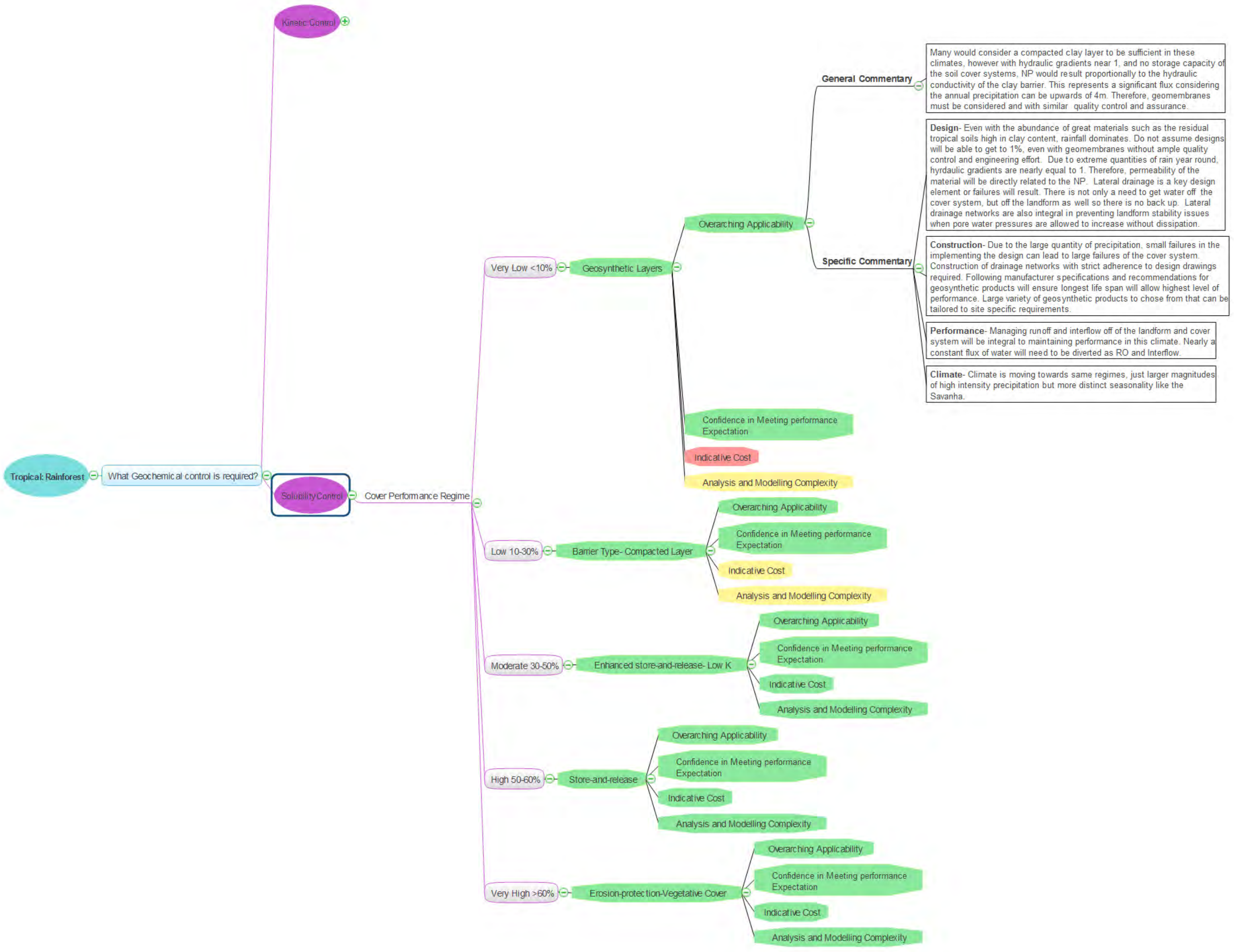
Design- This design strictly focuses on reductions of O2 ingress. The design exploits the large quantity of water available, residual soils suitable for vegetation establishment which provides erosion protection. Modeling should focus on maintaining high degrees of saturation to limit air permeability. Designs should anticipate the quantity of water removed from the cover system by climax vegetation to ensure the growth medium is adequately thick to maintain high degrees of saturation in the non rooting zones. Because the design is attempting to maintain high degrees of saturation in the cover system, landform design is also important to manage excess water to prevent liquidfaction of cover system materials.

Construction- Uncovered wastes are freely oxidizing, construction should try to get any amount of cover system material onto the facilities as soon as possible as this will significantly reduce oxygen ingress. Even the introduction of finer ROM between successive lifts can aid in increased moisture retention.

Performance- To see reductions in loading to the environment, shutting down oxygen is the easiest versus trying to control NP. Therefore, progressive cover system placement should strongly be considered for freshly placed waste material. All of the components of this design should be available to make this a relatively easy task.

Climate- Tropical climates are the most easily exploited in terms of managing oxygen ingress. The difficulty is in maintaining the balance between enough water to maintain high degrees of saturation versus shedding excessive water. With climate change, higher intensity precipitation events will be more common. This reinforces the need to promote and establish vegetation as soon as possible.

2.2 Tropical: Rainforest (NP)



Many would consider a compacted clay layer to be sufficient in these climates, however with hydraulic gradients near 1, and no storage capacity of the soil cover systems, NP would result proportionally to the hydraulic conductivity of the clay barrier. This represents a significant flux considering the annual precipitation can be upwards of 4m. Therefore, geomembranes must be considered and with similar quality control and assurance.

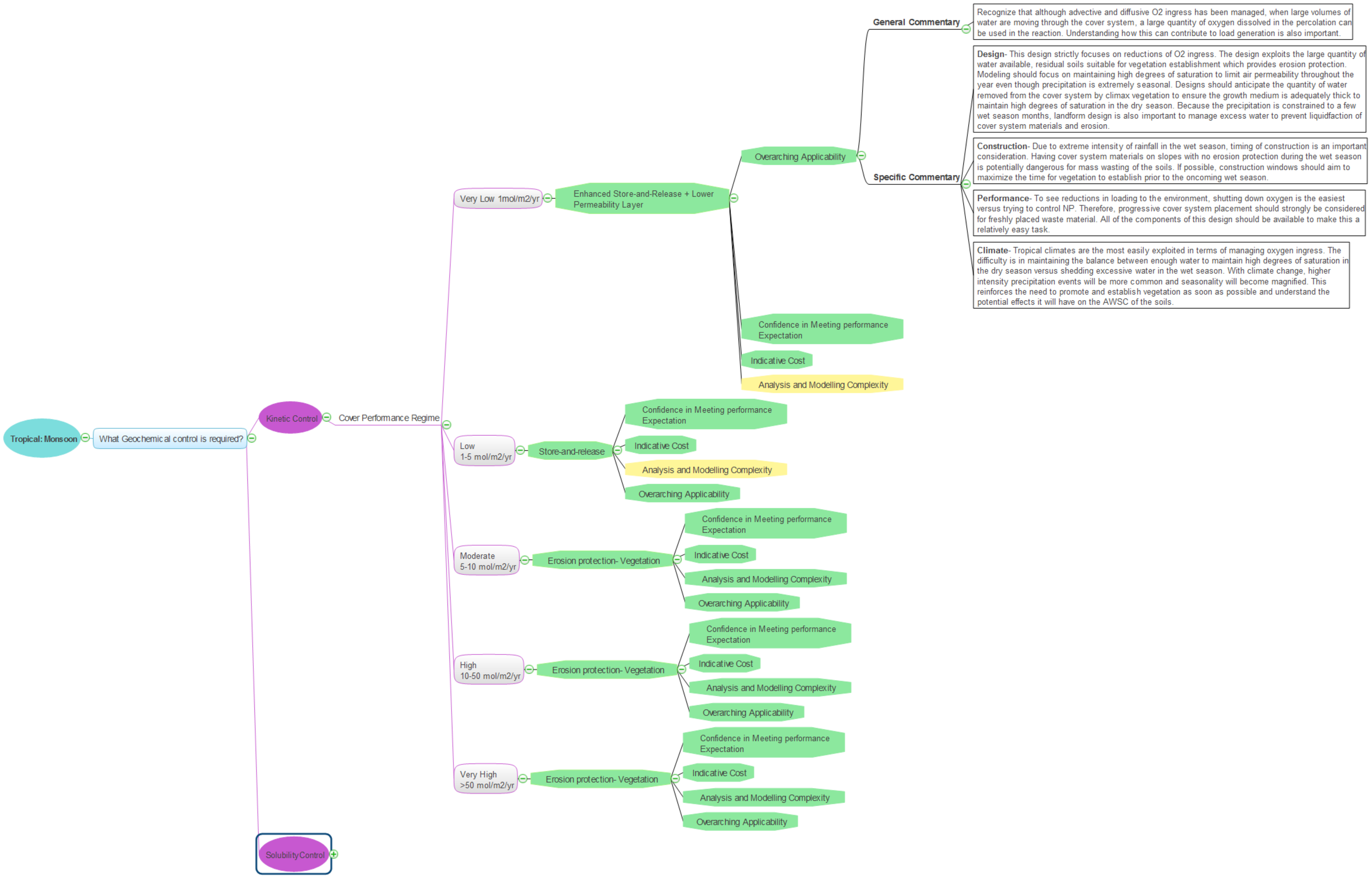
Design- Even with the abundance of great materials such as the residual tropical soils high in clay content, rainfall dominates. Do not assume designs will be able to get to 1%, even with geomembranes without ample quality control and engineering effort. Due to extreme quantities of rain year round, hyrdaulic gradients are nearly equal to 1. Therefore, permeability of the material will be directly related to the NP. Lateral drainage is a key design element or failures will result. There is not only a need to get water off the cover system, but off the landform as well so there is no back up. Lateral drainage networks are also integral in preventing landform stability issues when pore water pressures are allowed to increase without dissipation.

Construction- Due to the large quantity of precipitation, small failures in the implementing the design can lead to large failures of the cover system. Construction of drainage networks with strict adherence to design drawings required. Following manufacturer specifications and recommendations for geosynthetic products will ensure longest life span will allow highest level of performance. Large variety of geosynthetic products to chose from that can be tailored to site specific requirements.

Performance- Managing runoff and interflow off of the landform and cover system will be integral to maintaining performance in this climate. Nearly a constant flux of water will need to be diverted as RO and Interflow.

Climate- Climate is moving towards same regimes, just larger magnitudes of high intensity precipitation but more distinct seasonality like the Savanha.

2.3 Tropical: Monsoon (O_2)



Recognize that although advective and diffusive O2 ingress has been managed, when large volumes of water are moving through the cover system, a large quantity of oxygen dissolved in the percolation can be used in the reaction. Understanding how this can contribute to load generation is also important.

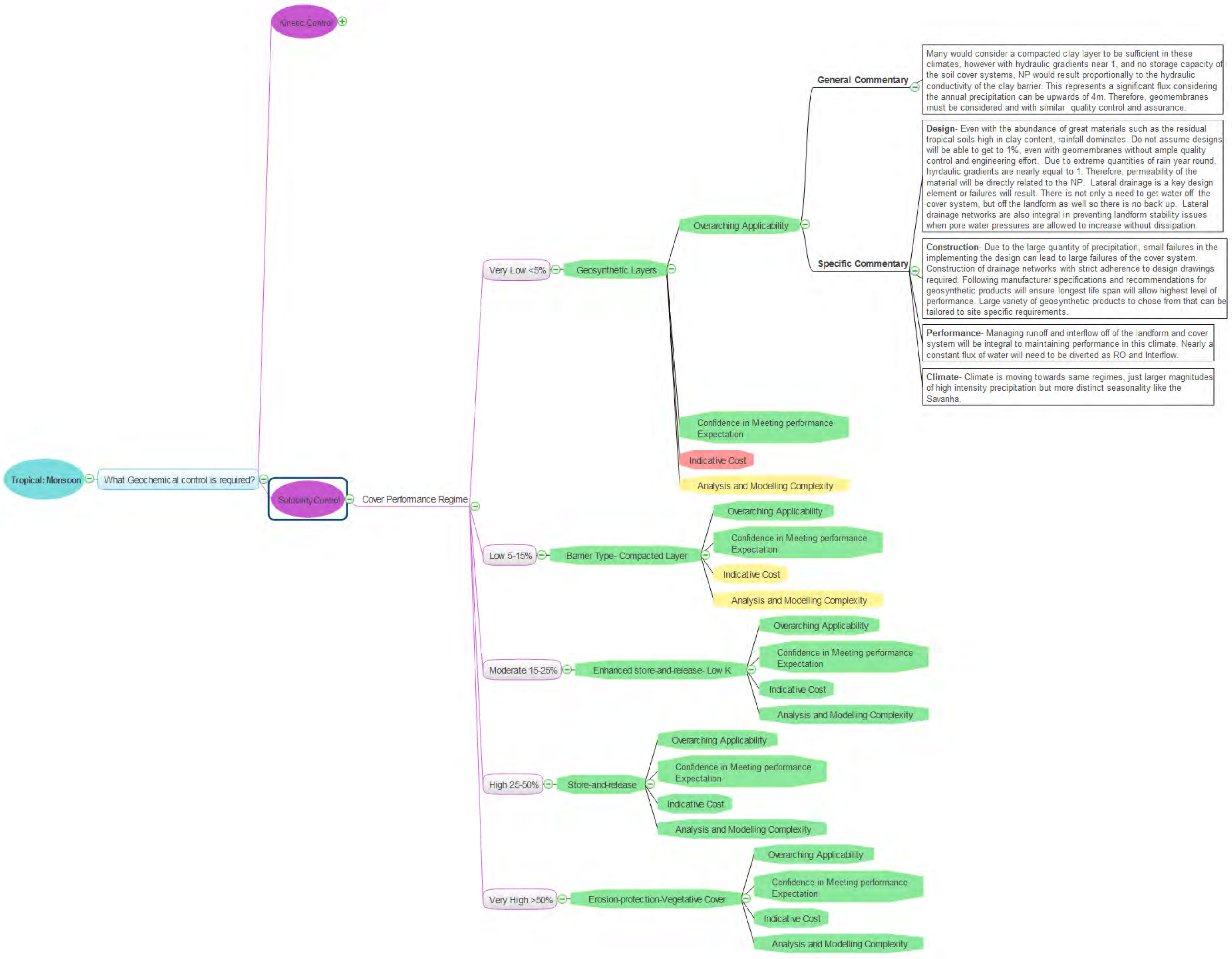
Design- This design strictly focuses on reductions of O2 ingress. The design exploits the large quantity of water available, residual soils suitable for vegetation establishment which provides erosion protection. Modeling should focus on maintaining high degrees of saturation to limit air permeability throughout the year even though precipitation is extremely seasonal. Designs should anticipate the quantity of water removed from the cover system by climax vegetation to ensure the growth medium is adequately thick to maintain high degrees of saturation in the dry season. Because the precipitation is constrained to a few wet season months, landform design is also important to manage excess water to prevent liquidfaction of cover system materials and erosion.

Construction- Due to extreme intensity of rainfall in the wet season, timing of construction is an important consideration. Having cover system materials on slopes with no erosion protection during the wet season is potentially dangerous for mass wasting of the soils. If possible, construction windows should aim to maximize the time for vegetation to establish prior to the oncoming wet season.

Performance- To see reductions in loading to the environment, shutting down oxygen is the easiest versus trying to control NP. Therefore, progressive cover system placement should strongly be considered for freshly placed waste material. All of the components of this design should be available to make this a relatively easy task.

Climate- Tropical climates are the most easily exploited in terms of managing oxygen ingress. The difficulty is in maintaining the balance between enough water to maintain high degrees of saturation in the dry season versus shedding excessive water in the wet season. With climate change, higher intensity precipitation events will be more common and seasonality will become magnified. This reinforces the need to promote and establish vegetation as soon as possible and understand the potential effects it will have on the AWSC of the soils.

2.4 Tropical: Monsoon (NP)



Many would consider a compacted clay layer to be sufficient in these climates, however with hydraulic gradients near 1, and no storage capacity of the soil cover systems, NP would result proportionally to the hydraulic conductivity of the clay barrier. This represents a significant flux considering the annual precipitation can be upwards of 4m. Therefore, geomembranes must be considered and with similar quality control and assurance.

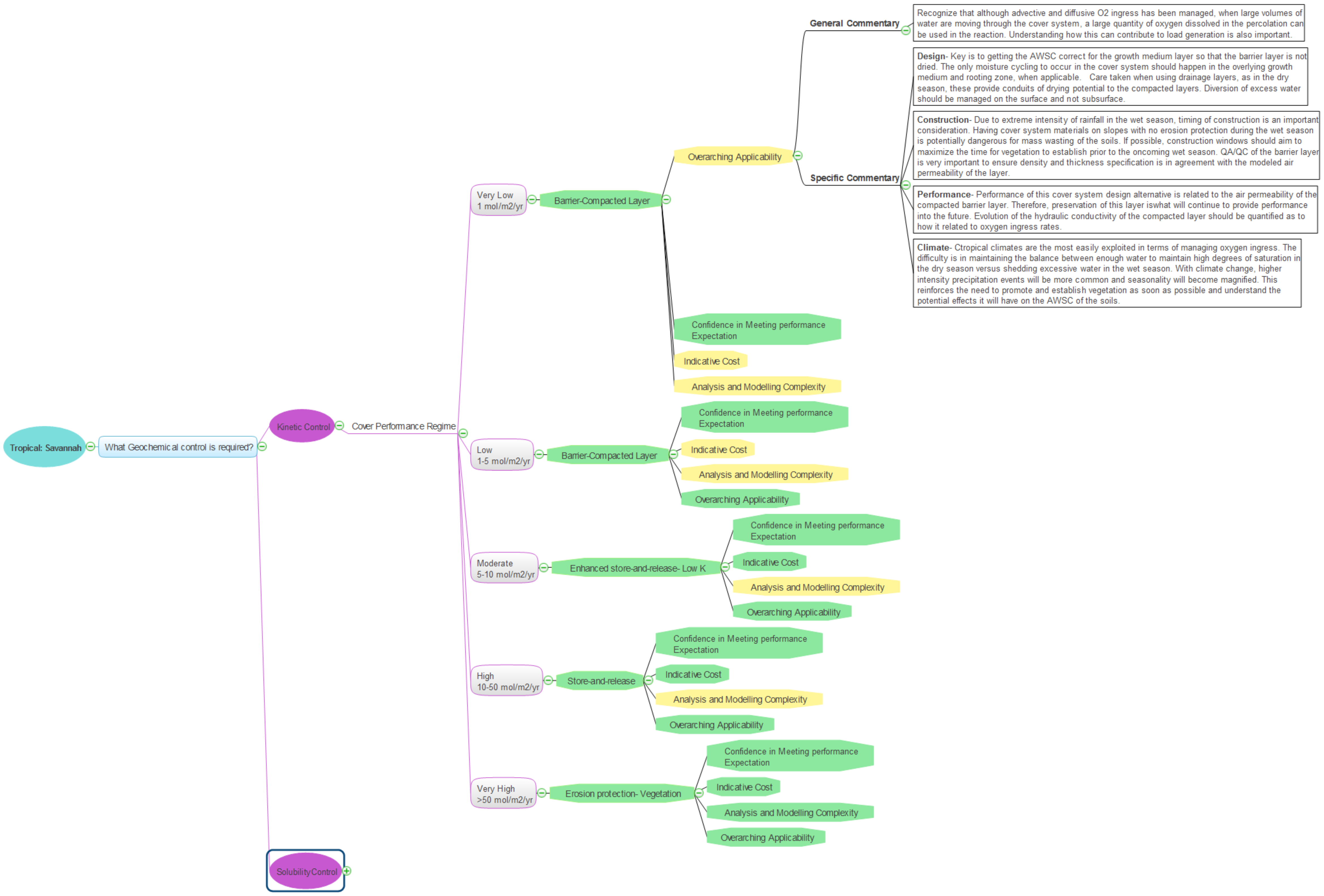
Design- Even with the abundance of great materials such as the residual tropical soils high in clay content, rainfall dominates. Do not assume designs will be able to get to 1%, even with geomembranes without ample quality control and engineering effort. Due to extreme quantities of rain year round, hyrdaulic gradients are nearly equal to 1. Therefore, permeability of the material will be directly related to the NP. Lateral drainage is a key design element or failures will result. There is not only a need to get water off the cover system, but off the landform as well so there is no back up. Lateral drainage networks are also integral in preventing landform stability issues when pore water pressures are allowed to increase without dissipation.

Construction- Due to the large quantity of precipitation, small failures in the implementing the design can lead to large failures of the cover system. Construction of drainage networks with strict adherence to design drawings required. Following manufacturer specifications and recommendations for geosynthetic products will ensure longest life span will allow highest level of performance. Large variety of geosynthetic products to chose from that can be tailored to site specific requirements.

Performance- Managing runoff and interflow off of the landform and cover system will be integral to maintaining performance in this climate. Nearly a constant flux of water will need to be diverted as RO and Interflow.

Climate- Climate is moving towards same regimes, just larger magnitudes of high intensity precipitation but more distinct seasonality like the Savanha.

2.5 Tropical: Savannah (O_2)



Recognize that although advective and diffusive O2 ingress has been managed, when large volumes of water are moving through the cover system, a large quantity of oxygen dissolved in the percolation can be used in the reaction. Understanding how this can contribute to load generation is also important.

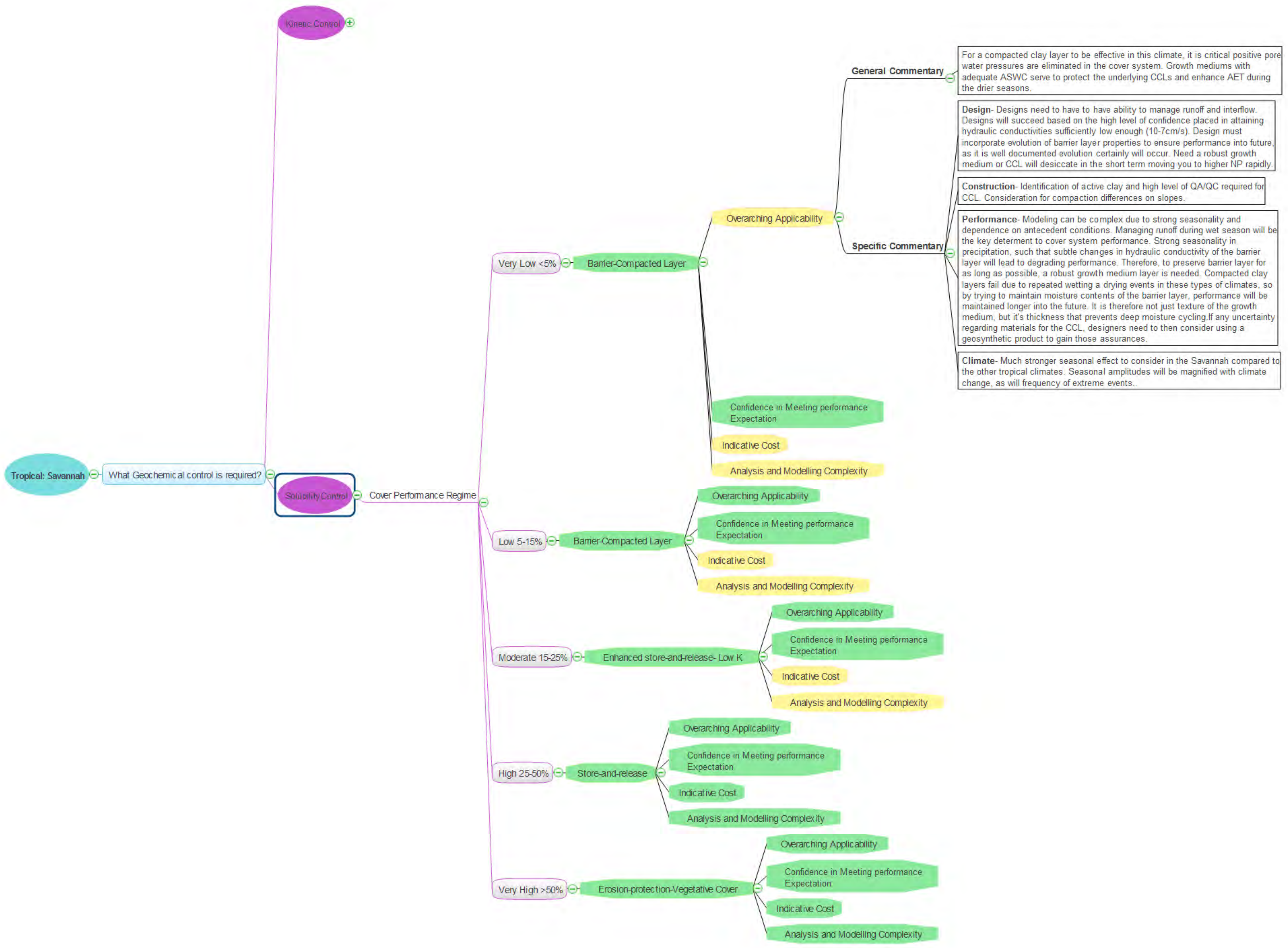
Design- Key is to getting the AWSC correct for the growth medium layer so that the barrier layer is not dried. The only moisture cycling to occur in the cover system should happen in the overlying growth medium and rooting zone, when applicable. Care taken when using drainage layers, as in the dry season, these provide conduits of drying potential to the compacted layers. Diversion of excess water should be managed on the surface and not subsurface.

Construction- Due to extreme intensity of rainfall in the wet season, timing of construction is an important consideration. Having cover system materials on slopes with no erosion protection during the wet season is potentially dangerous for mass wasting of the soils. If possible, construction windows should aim to maximize the time for vegetation to establish prior to the oncoming wet season. QA/QC of the barrier layer is very important to ensure density and thickness specification is in agreement with the modeled air permeability of the layer.

Performance- Performance of this cover system design alternative is related to the air permeability of the compacted barrier layer. Therefore, preservation of this layer iswhat will continue to provide performance into the future. Evolution of the hydraulic conductivity of the compacted layer should be quantified as to how it related to oxygen ingress rates.

Climate- Ctropical climates are the most easily exploited in terms of managing oxygen ingress. The difficulty is in maintaining the balance between enough water to maintain high degrees of saturation in the dry season versus shedding excessive water in the wet season. With climate change, higher intensity precipitation events will be more common and seasonality will become magnified. This reinforces the need to promote and establish vegetation as soon as possible and understand the potential effects it will have on the AWSC of the soils.

2.6 Tropical: Savannah (NP)



For a compacted clay layer to be effective in this climate, it is critical positive pore water pressures are eliminated in the cover system. Growth mediums with adequate ASWC serve to protect the underlying CCLs and enhance AET during the drier seasons.

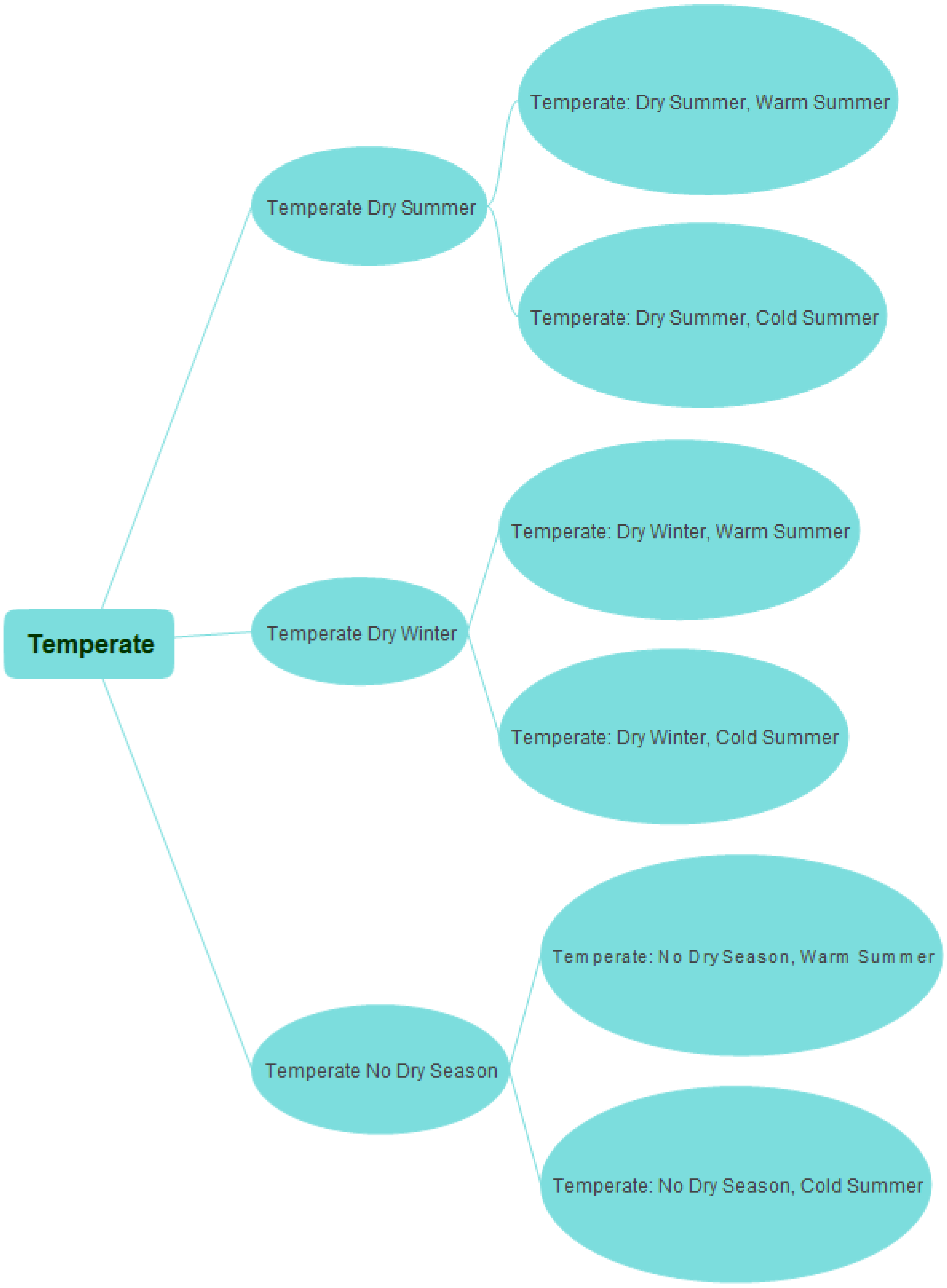
Design- Designs need to have to have ability to manage runoff and interflow. Designs will succeed based on the high level of confidence placed in attaining hydraulic conductivities sufficiently low enough (10-7cm/s). Design must incorporate evolution of barrier layer properties to ensure performance into future, as it is well documented evolution certainly will occur. Need a robust growth medium or CCL will desiccate in the short term moving you to higher NP rapidly.

Construction- Identification of active clay and high level of QA/QC required for CCL. Consideration for compaction differences on slopes.

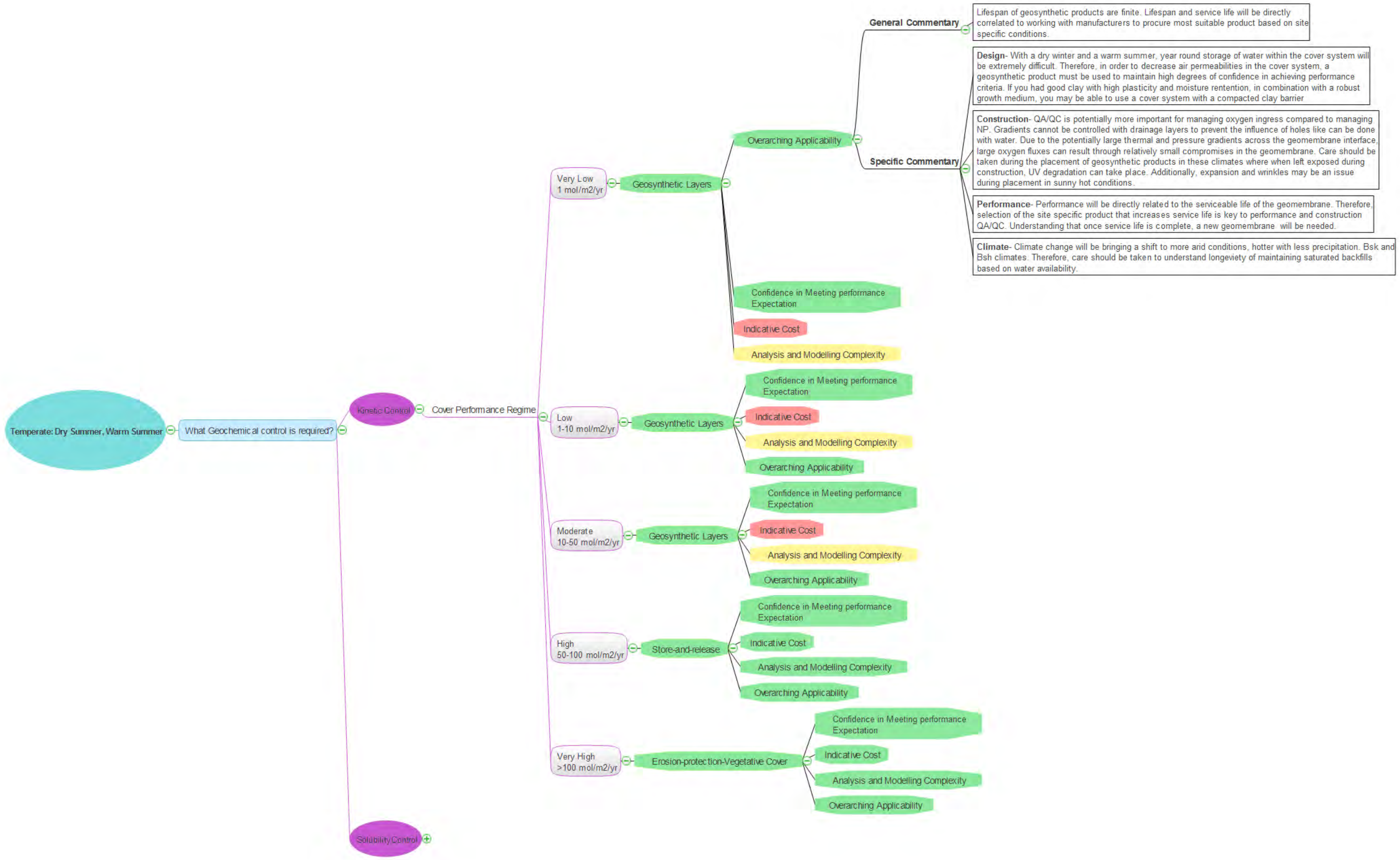
Performance- Modeling can be complex due to strong seasonality and dependence on antecedent conditions. Managing runoff during wet season will be the key determent to cover system performance. Strong seasonality in precipitation, such that subtle changes in hydraulic conductivity of the barrier layer will lead to degrading performance. Therefore, to preserve barrier layer for as long as possible, a robust growth medium layer is needed. Compacted clay layers fail due to repeated wetting a drying events in these types of climates, so by trying to maintain moisture contents of the barrier layer, performance will be maintained longer into the future. It is therefore not just texture of the growth medium, but it's thickness that prevents deep moisture cycling.If any uncertainty regarding materials for the CCL, designers need to then consider using a geosynthetic product to gain those assurances.

Climate- Much stronger seasonal effect to consider in the Savannah compared to the other tropical climates. Seasonal amplitudes will be magnified with climate change, as will frequency of extreme events..

3 TEMPERATE CLIMATE OVERVIEW



3.1 Temperate: Dry Summer, Warm Summer (O_2)



Lifespan of geosynthetic products are finite. Lifespan and service life will be directly correlated to working with manufacturers to procure most suitable product based on site specific conditions.

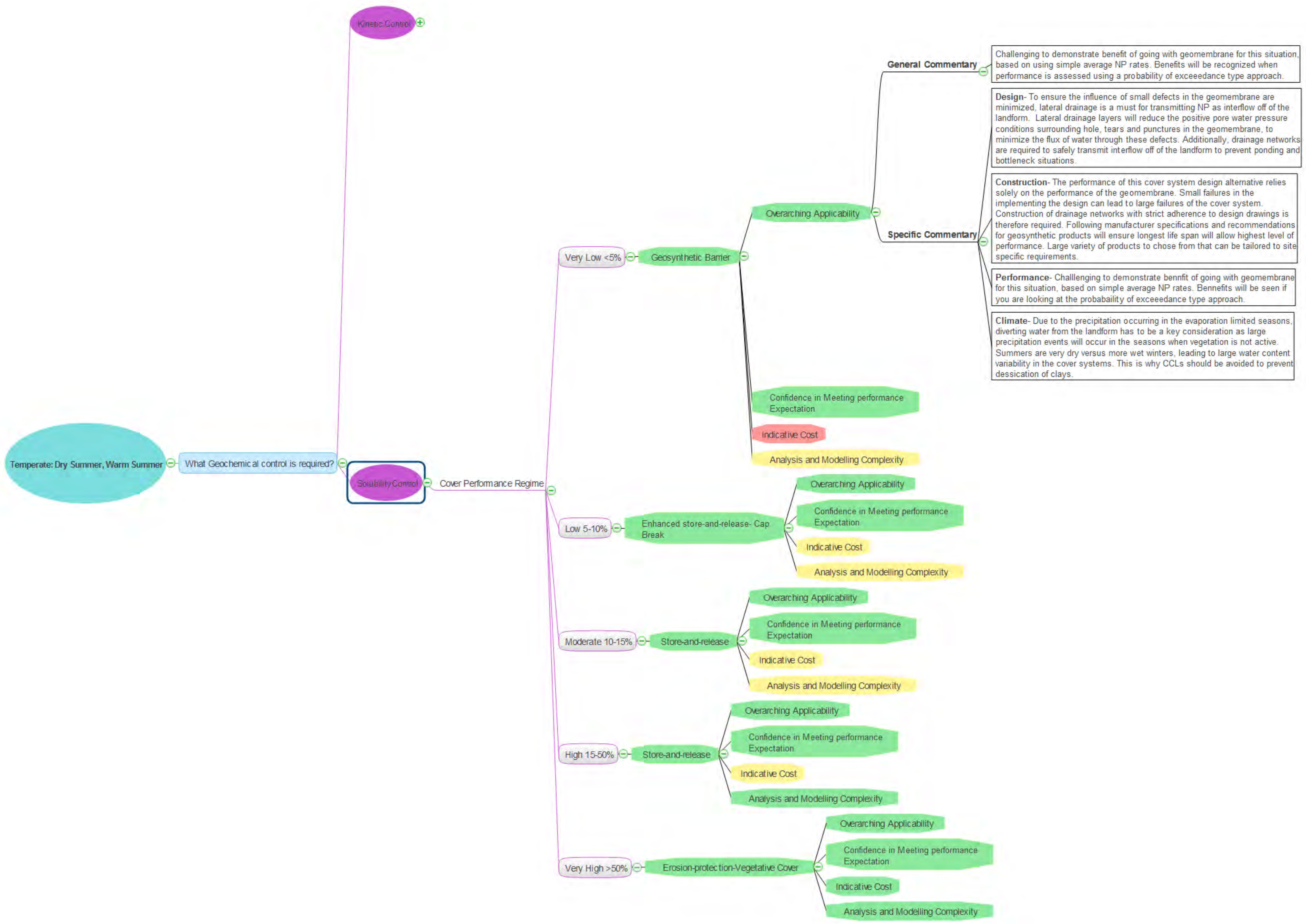
Design- With a dry winter and a warm summer, year round storage of water within the cover system will be extremely difficult. Therefore, in order to decrease air permeabilities in the cover system, a geosynthetic product must be used to maintain high degrees of confidence in achieving performance criteria. If you had good clay with high plasticity and moisture rentention, in combination with a robust growth medium, you may be able to use a cover system with a compacted clay barrier

Construction- QA/QC is potentially more important for managing oxygen ingress compared to managing NP. Gradients cannot be controlled with drainage layers to prevent the influence of holes like can be done with water. Due to the potentially large thermal and pressure gradients across the geomembrane interface, large oxygen fluxes can result through relatively small compromises in the geomembrane. Care should be taken during the placement of geosynthetic products in these climates where when left exposed during construction, UV degradation can take place. Additionally, expansion and wrinkles may be an issue during placement in sunny hot conditions.

Performance- Performance will be directly related to the serviceable life of the geomembrane. Therefore, selection of the site specific product that increases service life is key to performance and construction QA/QC. Understanding that once service life is complete, a new geomembrane will be needed.

Climate- Climate change will be bringing a shift to more arid conditions, hotter with less precipitation. Bsk and Bsh climates. Therefore, care should be taken to understand longeviety of maintaining saturated backfills based on water availability.

3.2 Temperate: Dry Summer, Warm Summer (NP)



Challenging to demonstrate benefit of going with geomembrane for this situation, based on using simple average NP rates. Benefits will be recognized when performance is assessed using a probability of exceeedance type approach.

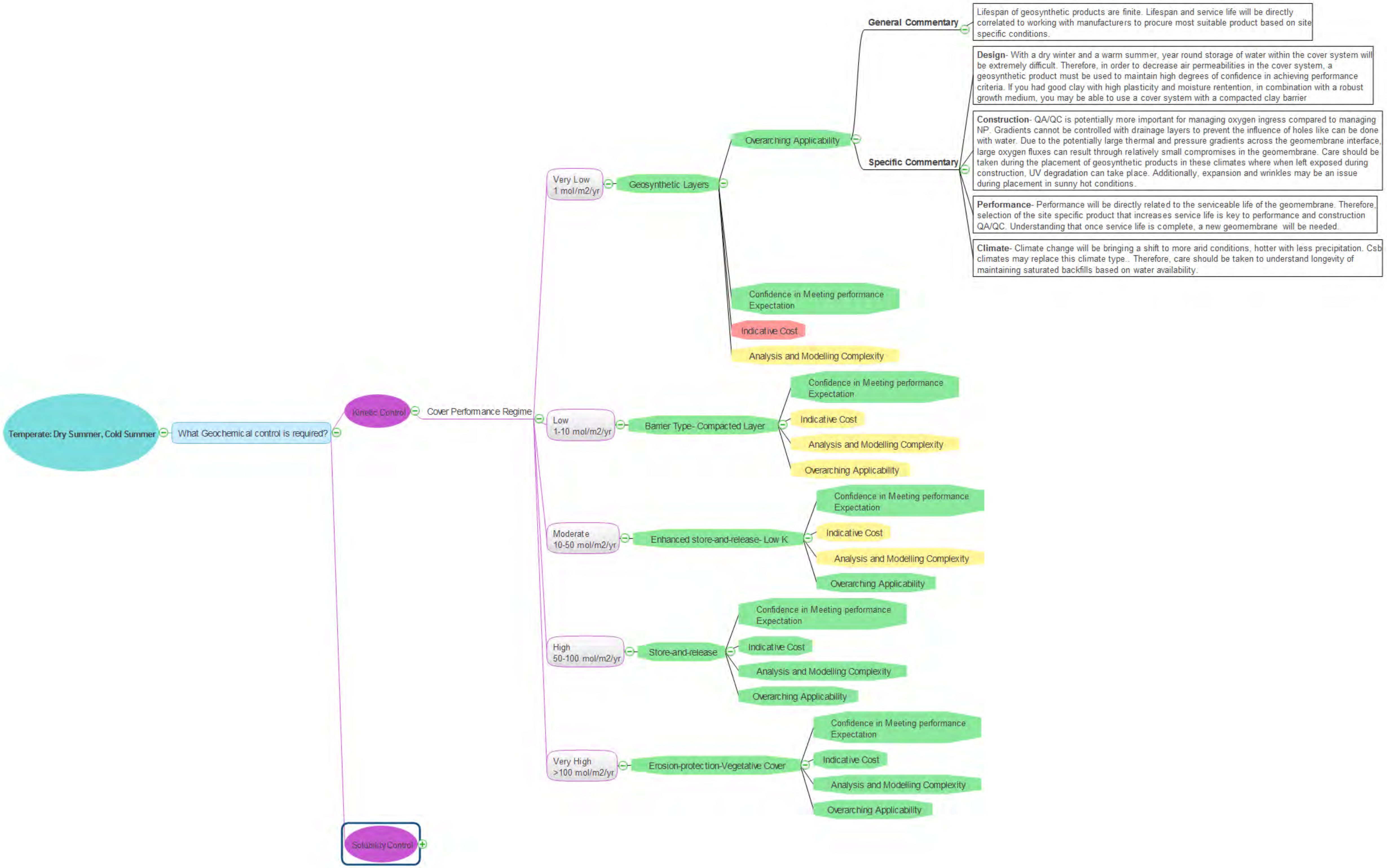
Design- To ensure the influence of small defects in the geomembrane are minimized, lateral drainage is a must for transmitting NP as interflow off of the landform. Lateral drainage layers will reduce the positive pore water pressure conditions surrounding hole, tears and punctures in the geomembrane, to minimize the flux of water through these defects. Additionally, drainage networks are required to safely transmit interflow off of the landform to prevent ponding and bottleneck situations.

Construction- The performance of this cover system design alternative relies solely on the performance of the geomembrane. Small failures in the implementing the design can lead to large failures of the cover system. Construction of drainage networks with strict adherence to design drawings is therefore required. Following manufacturer specifications and recommendations for geosynthetic products will ensure longest life span will allow highest level of performance. Large variety of products to chose from that can be tailored to site specific requirements.

Performance- Challlenging to demonstrate bennfit of going with geomembrane for this situation, based on simple average NP rates. Bennefits will be seen if you are looking at the probabaility of exceeedance type approach.

Climate- Due to the precipitation occurring in the evaporation limited seasons, diverting water from the landform has to be a key consideration as large precipitation events will occur in the seasons when vegetation is not active. Summers are very dry versus more wet winters, leading to large water content variability in the cover systems. This is why CCLs should be avoided to prevent dessication of clays.

3.3 Temperate: Dry Summer, Cold Summer (O_2)



Lifespan of geosynthetic products are finite. Lifespan and service life will be directly correlated to working with manufacturers to procure most suitable product based on site specific conditions.

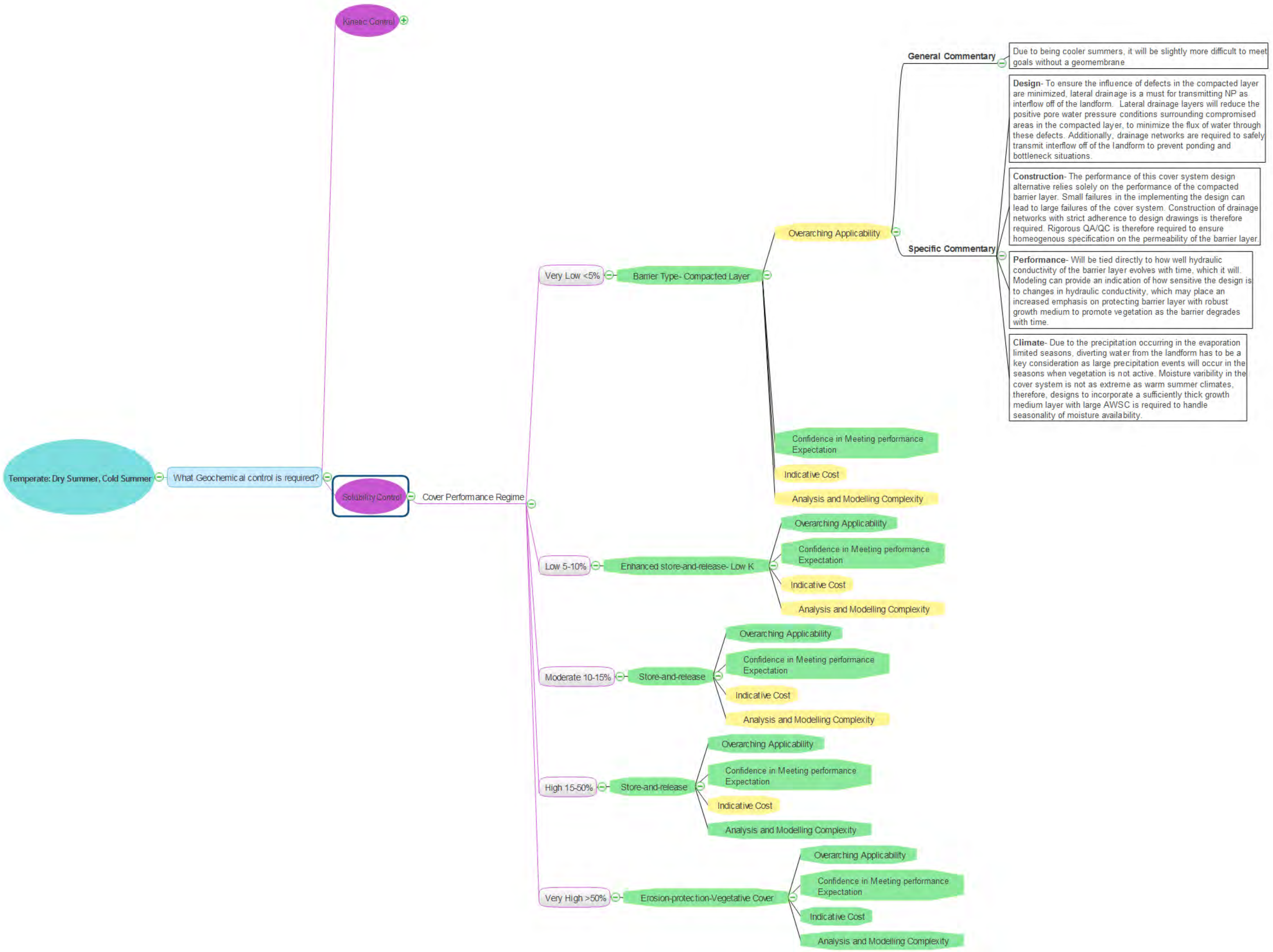
Design- With a dry winter and a warm summer, year round storage of water within the cover system will be extremely difficult. Therefore, in order to decrease air permeabilities in the cover system, a geosynthetic product must be used to maintain high degrees of confidence in achieving performance criteria. If you had good clay with high plasticity and moisture rentention, in combination with a robust growth medium, you may be able to use a cover system with a compacted clay barrier

Construction- QA/QC is potentially more important for managing oxygen ingress compared to managing NP. Gradients cannot be controlled with drainage layers to prevent the influence of holes like can be done with water. Due to the potentially large thermal and pressure gradients across the geomembrane interface, large oxygen fluxes can result through relatively small compromises in the geomembrane. Care should be taken during the placement of geosynthetic products in these climates where when left exposed during construction, UV degradation can take place. Additionally, expansion and wrinkles may be an issue during placement in sunny hot conditions.

Performance- Performance will be directly related to the serviceable life of the geomembrane. Therefore, selection of the site specific product that increases service life is key to performance and construction QA/QC. Understanding that once service life is complete, a new geomembrane will be needed.

Climate- Climate change will be bringing a shift to more arid conditions, hotter with less precipitation. Csb climates may replace this climate type.. Therefore, care should be taken to understand longevity of maintaining saturated backfills based on water availability.

3.4 Temperate: Dry Summer, Cold Summer (NP)



Due to being cooler summers, it will be slightly more difficult to meet goals without a geomembrane

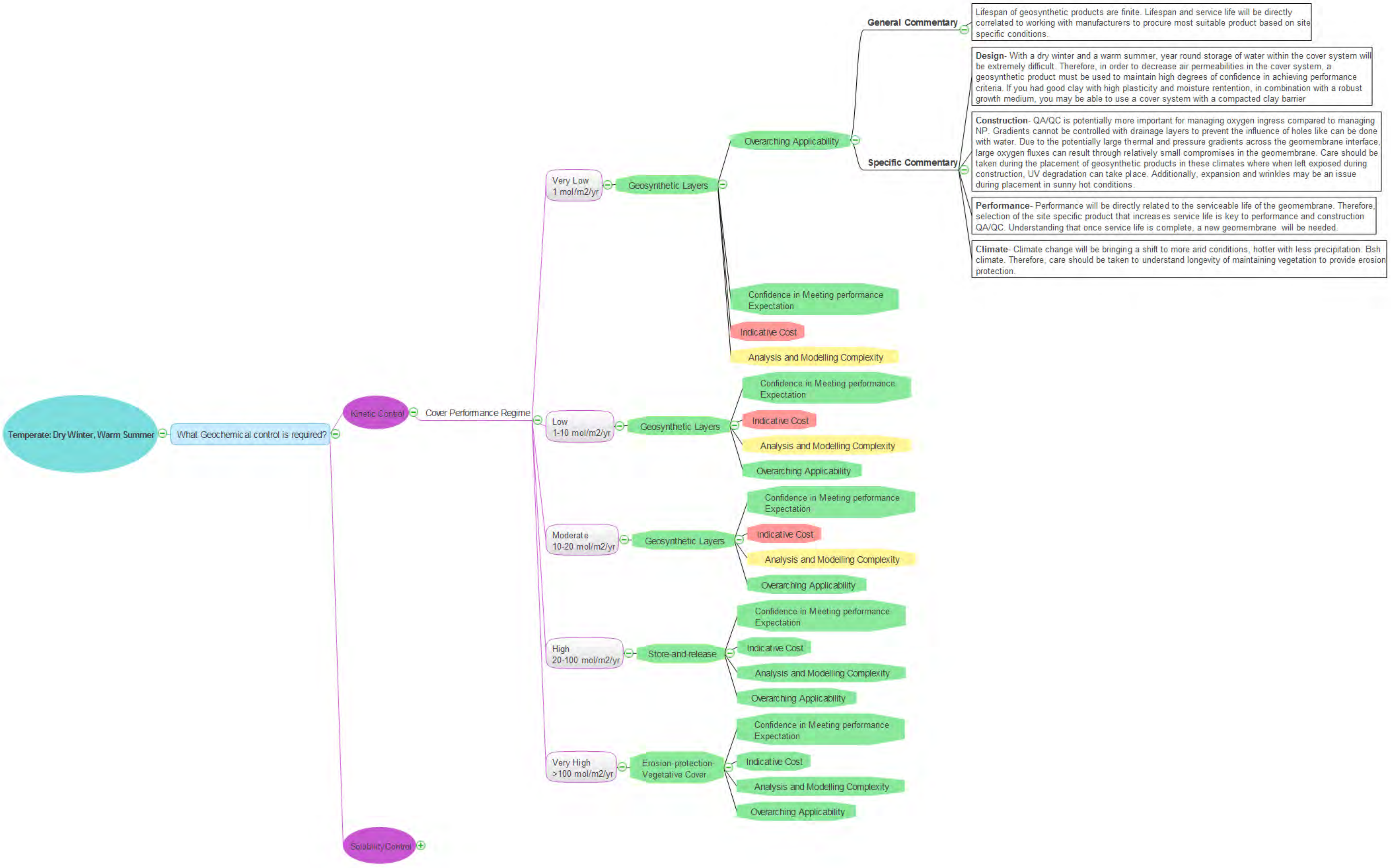
Design- To ensure the influence of defects in the compacted layer are minimized, lateral drainage is a must for transmitting NP as interflow off of the landform. Lateral drainage layers will reduce the positive pore water pressure conditions surrounding compromised areas in the compacted layer, to minimize the flux of water through these defects. Additionally, drainage networks are required to safely transmit interflow off of the landform to prevent ponding and bottleneck situations.

Construction- The performance of this cover system design alternative relies solely on the performance of the compacted barrier layer. Small failures in the implementing the design can lead to large failures of the cover system. Construction of drainage networks with strict adherence to design drawings is therefore required. Rigorous QA/QC is therefore required to ensure homeogenous specification on the permeability of the barrier layer.

Performance- Will be tied directly to how well hydraulic conductivity of the barrier layer evolves with time, which it will. Modeling can provide an indication of how sensitive the design is to changes in hydraulic conductivity, which may place an increased emphasis on protecting barrier layer with robust growth medium to promote vegetation as the barrier degrades with time.

Climate- Due to the precipitation occurring in the evaporation limited seasons, diverting water from the landform has to be a key consideration as large precipitation events will occur in the seasons when vegetation is not active. Moisture varibility in the cover system is not as extreme as warm summer climates, therefore, designs to incorporate a sufficiently thick growth medium layer with large AWSC is required to handle seasonality of moisture availability.

3.5 Temperate: Dry Winter, Warm Summer (O_2)



Lifespan of geosynthetic products are finite. Lifespan and service life will be directly correlated to working with manufacturers to procure most suitable product based on site specific conditions.

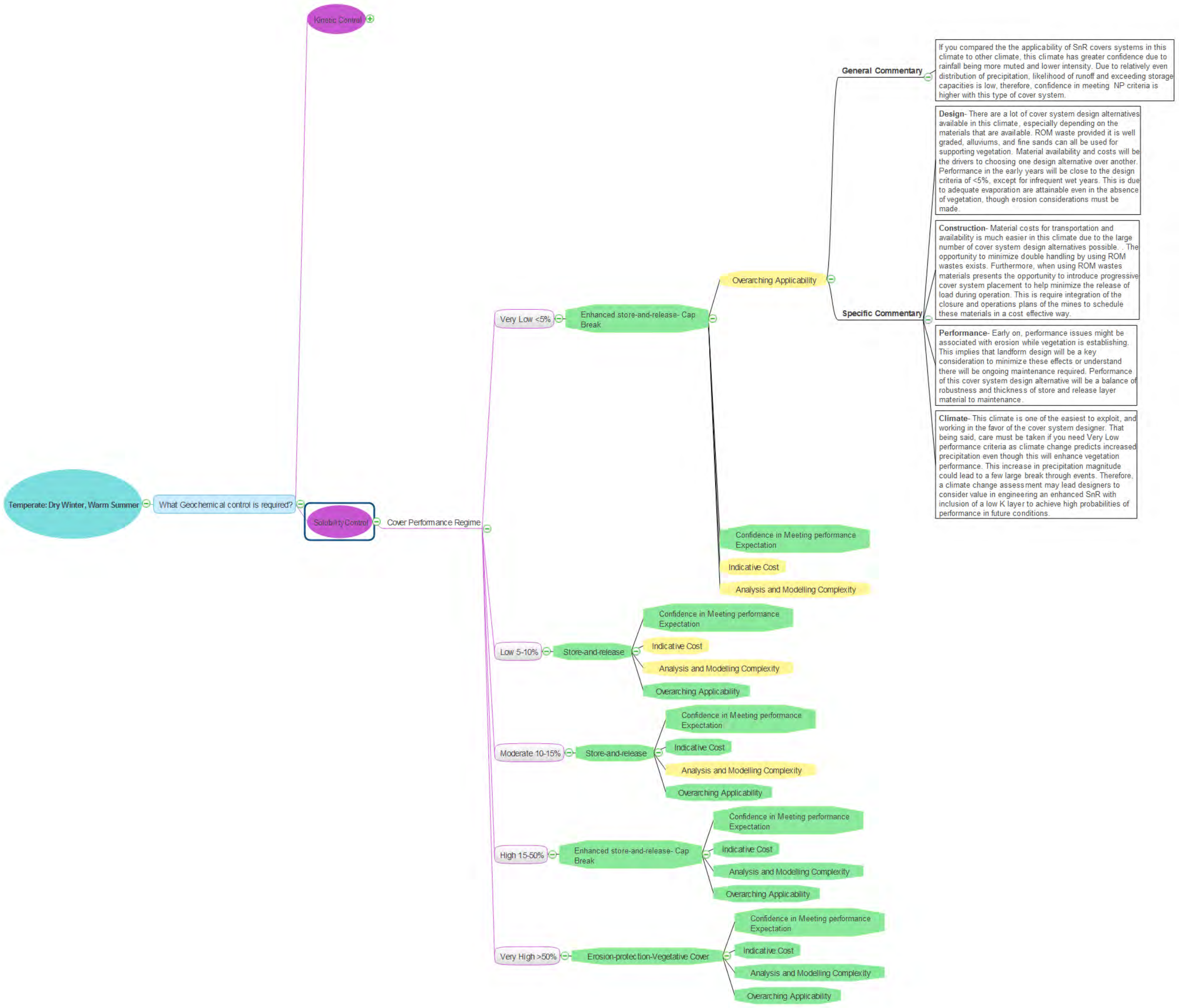
Design- With a dry winter and a warm summer, year round storage of water within the cover system will be extremely difficult. Therefore, in order to decrease air permeabilities in the cover system, a geosynthetic product must be used to maintain high degrees of confidence in achieving performance criteria. If you had good clay with high plasticity and moisture rentention, in combination with a robust growth medium, you may be able to use a cover system with a compacted clay barrier

Construction- QA/QC is potentially more important for managing oxygen ingress compared to managing NP. Gradients cannot be controlled with drainage layers to prevent the influence of holes like can be done with water. Due to the potentially large thermal and pressure gradients across the geomembrane interface, large oxygen fluxes can result through relatively small compromises in the geomembrane. Care should be taken during the placement of geosynthetic products in these climates where when left exposed during construction, UV degradation can take place. Additionally, expansion and wrinkles may be an issue during placement in sunny hot conditions.

Performance- Performance will be directly related to the serviceable life of the geomembrane. Therefore, selection of the site specific product that increases service life is key to performance and construction QA/QC. Understanding that once service life is complete, a new geomembrane will be needed.

Climate- Climate change will be bringing a shift to more arid conditions, hotter with less precipitation. Bsh climate. Therefore, care should be taken to understand longevity of maintaining vegetation to provide erosion protection.

3.6 Temperate: Dry Winter, Warm Summer (NP)



If you compared the the applicability of SnR covers systems in this climate to other climate, this climate has greater confidence due to rainfall being more muted and lower intensity. Due to relatively even distribution of precipitation, likelihood of runoff and exceeding storage capacities is low, therefore, confidence in meeting NP criteria is higher with this type of cover system.

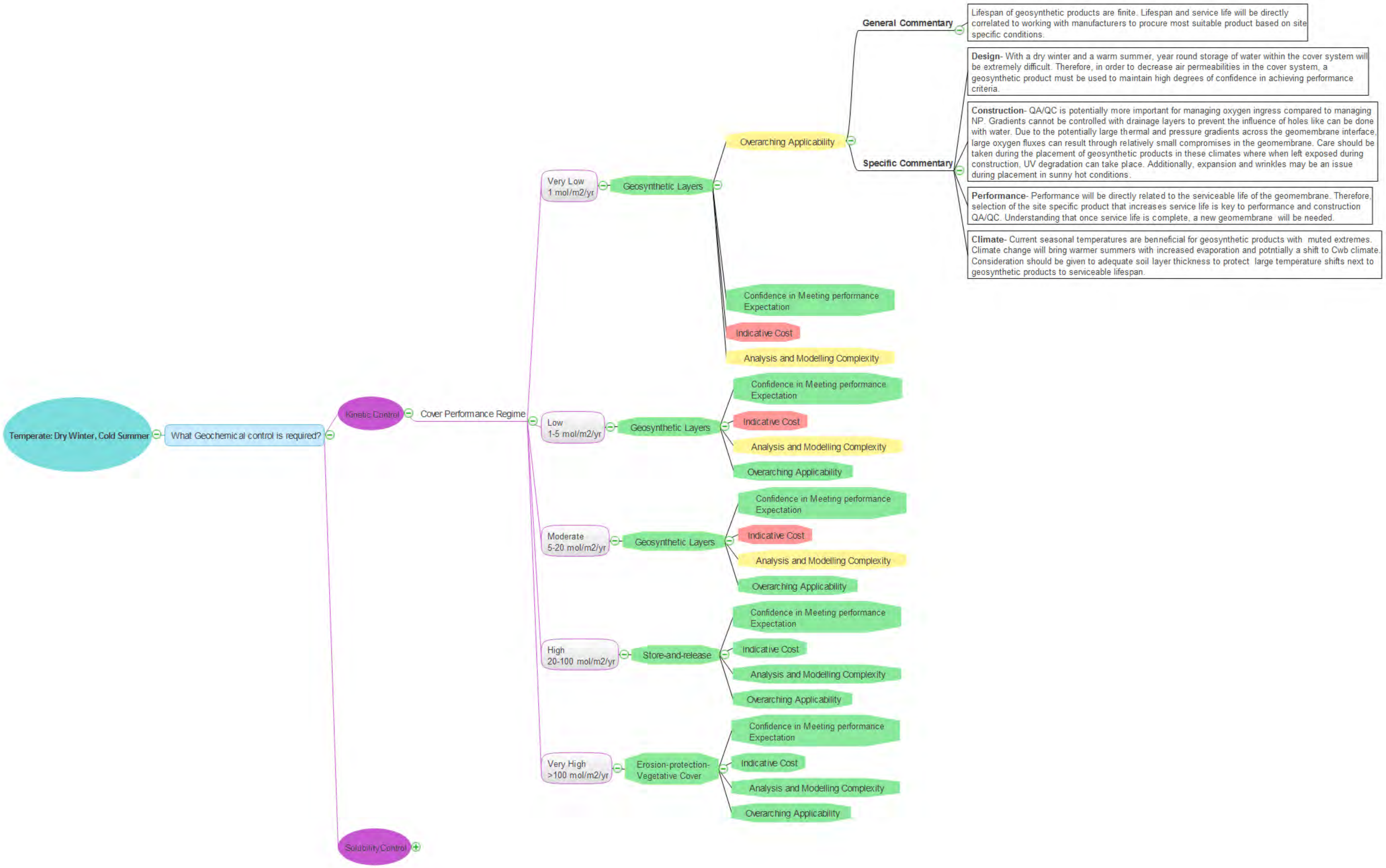
Design- There are a lot of cover system design alternatives available in this climate, especially depending on the materials that are available. ROM waste provided it is well graded, alluviums, and fine sands can all be used for supporting vegetation. Material availability and costs will be the drivers to choosing one design alternative over another. Performance in the early years will be close to the design criteria of <5%, except for infrequent wet years. This is due to adequate evaporation are attainable even in the absence of vegetation, though erosion considerations must be made.

Construction- Material costs for transportation and availability is much easier in this climate due to the large number of cover system design alternatives possible. . The opportunity to minimize double handling by using ROM wastes exists. Furthermore, when using ROM wastes materials presents the opportunity to introduce progressive cover system placement to help minimize the release of load during operation. This is require integration of the closure and operations plans of the mines to schedule these materials in a cost effective way.

Performance- Early on, performance issues might be associated with erosion while vegetation is establishing. This implies that landform design will be a key consideration to minimize these effects or understand there will be ongoing maintenance required. Performance of this cover system design alternative will be a balance of robustness and thickness of store and release layer material to maintenance.

Climate- This climate is one of the easiest to exploit, and working in the favor of the cover system designer. That being said, care must be taken if you need Very Low performance criteria as climate change predicts increased precipitation even though this will enhance vegetation performance. This increase in precipitation magnitude could lead to a few large break through events. Therefore, a climate change assessment may lead designers to consider value in engineering an enhanced SnR with inclusion of a low K layer to achieve high probabilities of performance in future conditions.

3.7 Temperate: Dry Winter, Cold Summer (O_2)



General Commentary

Lifespan of geosynthetic products are finite. Lifespan and service life will be directly correlated to working with manufacturers to procure most suitable product based on site specific conditions.

Specific Commentary

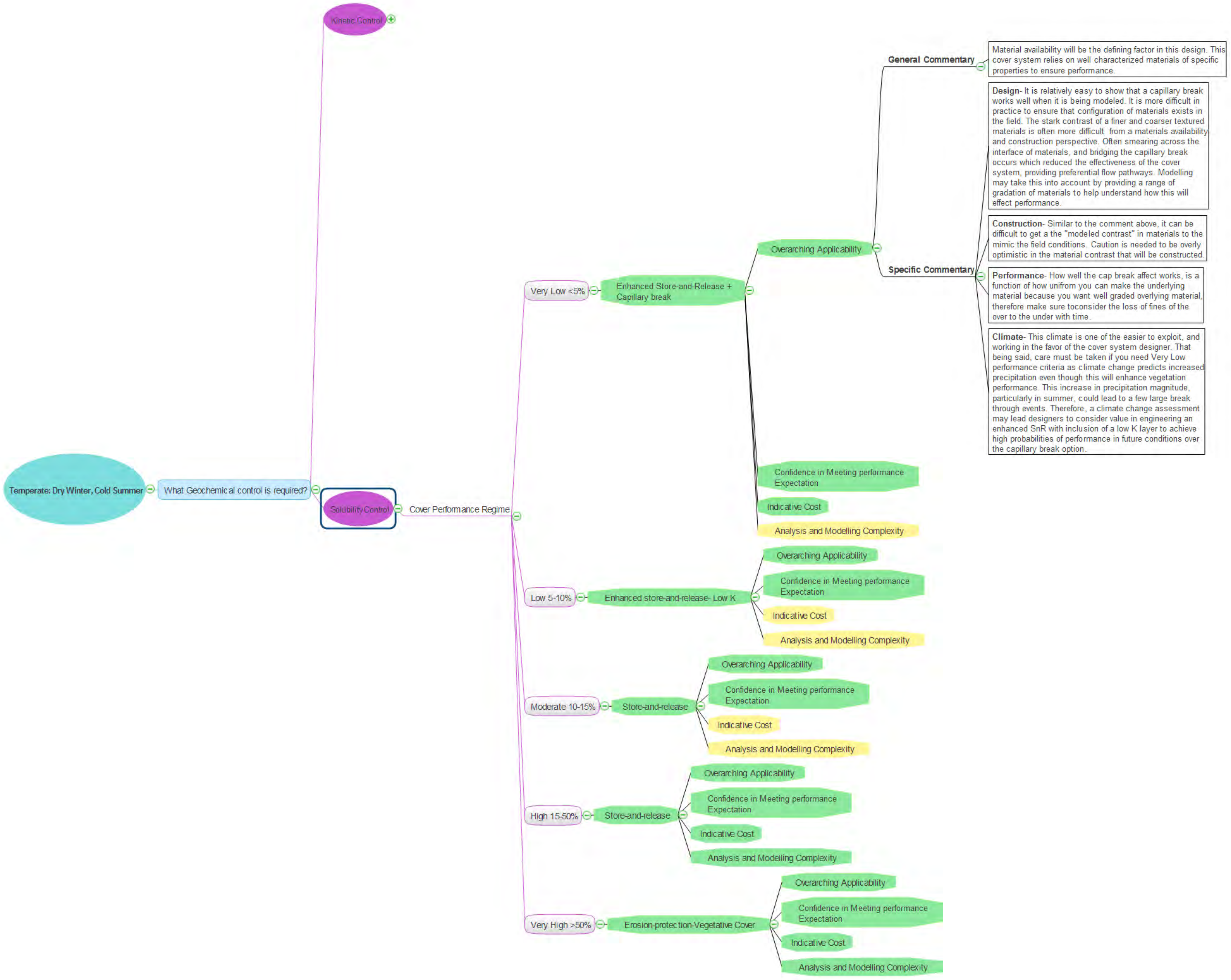
Design- With a dry winter and a warm summer, year round storage of water within the cover system will be extremely difficult. Therefore, in order to decrease air permeabilities in the cover system, a geosynthetic product must be used to maintain high degrees of confidence in achieving performance criteria.

Construction- QA/QC is potentially more important for managing oxygen ingress compared to managing NP. Gradients cannot be controlled with drainage layers to prevent the influence of holes like can be done with water. Due to the potentially large thermal and pressure gradients across the geomembrane interface, large oxygen fluxes can result through relatively small compromises in the geomembrane. Care should be taken during the placement of geosynthetic products in these climates where when left exposed during construction, UV degradation can take place. Additionally, expansion and wrinkles may be an issue during placement in sunny hot conditions.

Performance- Performance will be directly related to the serviceable life of the geomembrane. Therefore, selection of the site specific product that increases service life is key to performance and construction QA/QC. Understanding that once service life is complete, a new geomembrane will be needed.

Climate- Current seasonal temperatures are benneficial for geosynthetic products with muted extremes. Climate change will bring warmer summers with increased evaporation and potntially a shift to Cwb climate. Consideration should be given to adequate soil layer thickness to protect large temperature shifts next to geosynthetic products to serviceable lifespan.

3.8 Temperate: Dry Winter, Cold Summer (NP)



Material availability will be the defining factor in this design. This cover system relies on well characterized materials of specific properties to ensure performance.

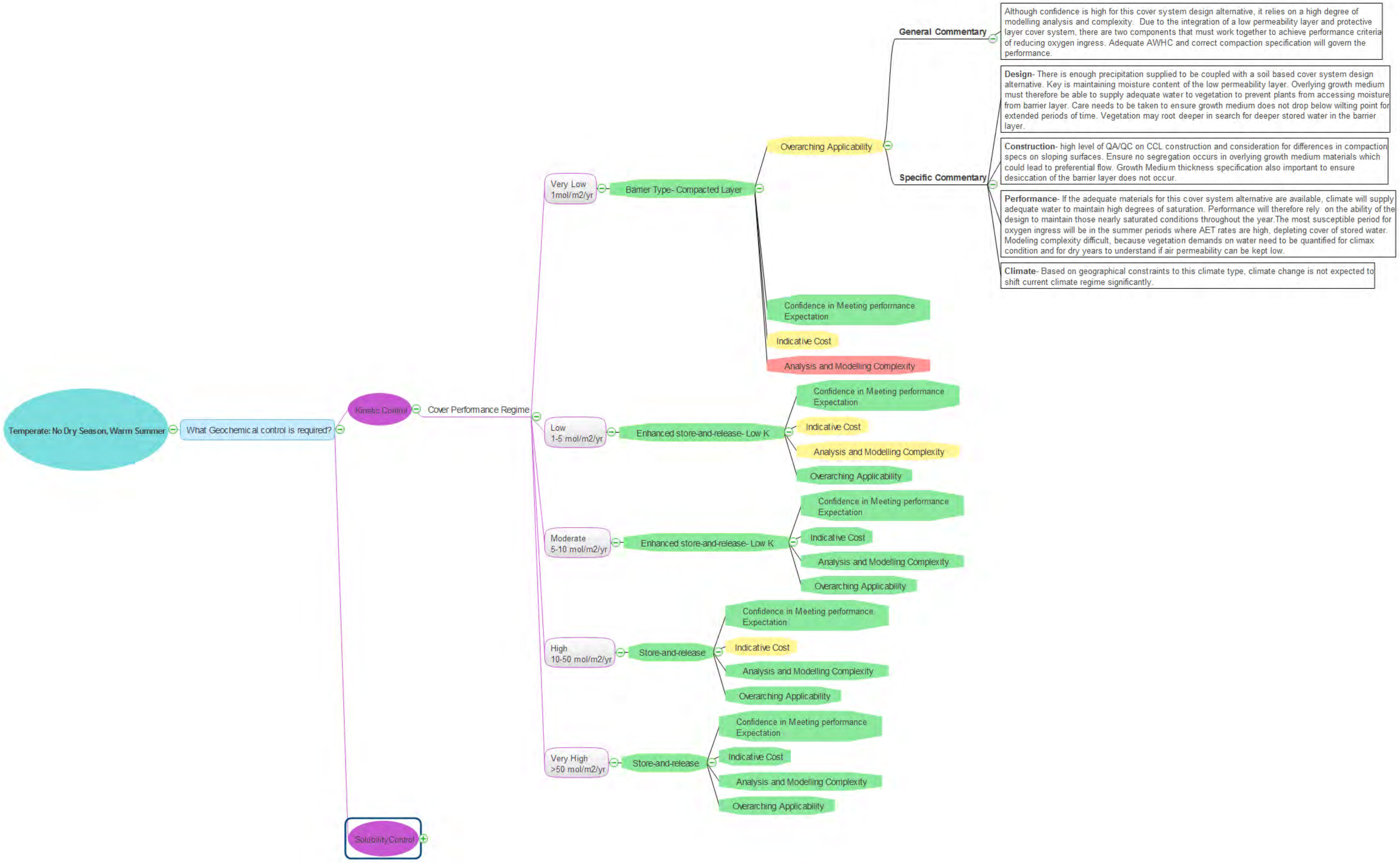
Design- It is relatively easy to show that a capillary break works well when it is being modeled. It is more difficult in practice to ensure that configuration of materials exists in the field. The stark contrast of a finer and coarser textured materials is often more difficult from a materials availability and construction perspective. Often smearing across the interface of materials, and bridging the capillary break occurs which reduced the effectiveness of the cover system, providing preferential flow pathways. Modelling may take this into account by providing a range of gradation of materials to help understand how this will effect performance.

Construction- Similar to the comment above, it can be difficult to get a the "modeled contrast" in materials to the mimic the field conditions. Caution is needed to be overly optimistic in the material contrast that will be constructed.

Performance- How well the cap break affect works, is a function of how unifrom you can make the underlying material because you want well graded overlying material, therefore make sure toconsider the loss of fines of the over to the under with time.

Climate- This climate is one of the easier to exploit, and working in the favor of the cover system designer. That being said, care must be taken if you need Very Low performance criteria as climate change predicts increased precipitation even though this will enhance vegetation performance. This increase in precipitation magnitude, particularly in summer, could lead to a few large break through events. Therefore, a climate change assessment may lead designers to consider value in engineering an enhanced SnR with inclusion of a low K layer to achieve high probabilities of performance in future conditions over the capillary break option.

3.9 Temperate: No Dry Season, Warm Summer (O_2)



Although confidence is high for this cover system design alternative, it relies on a high degree of modelling analysis and complexity. Due to the integration of a low permeability layer and protective layer cover system, there are two components that must work together to achieve performance criteria of reducing oxygen ingress. Adequate AWHC and correct compaction specification will govern the performance.

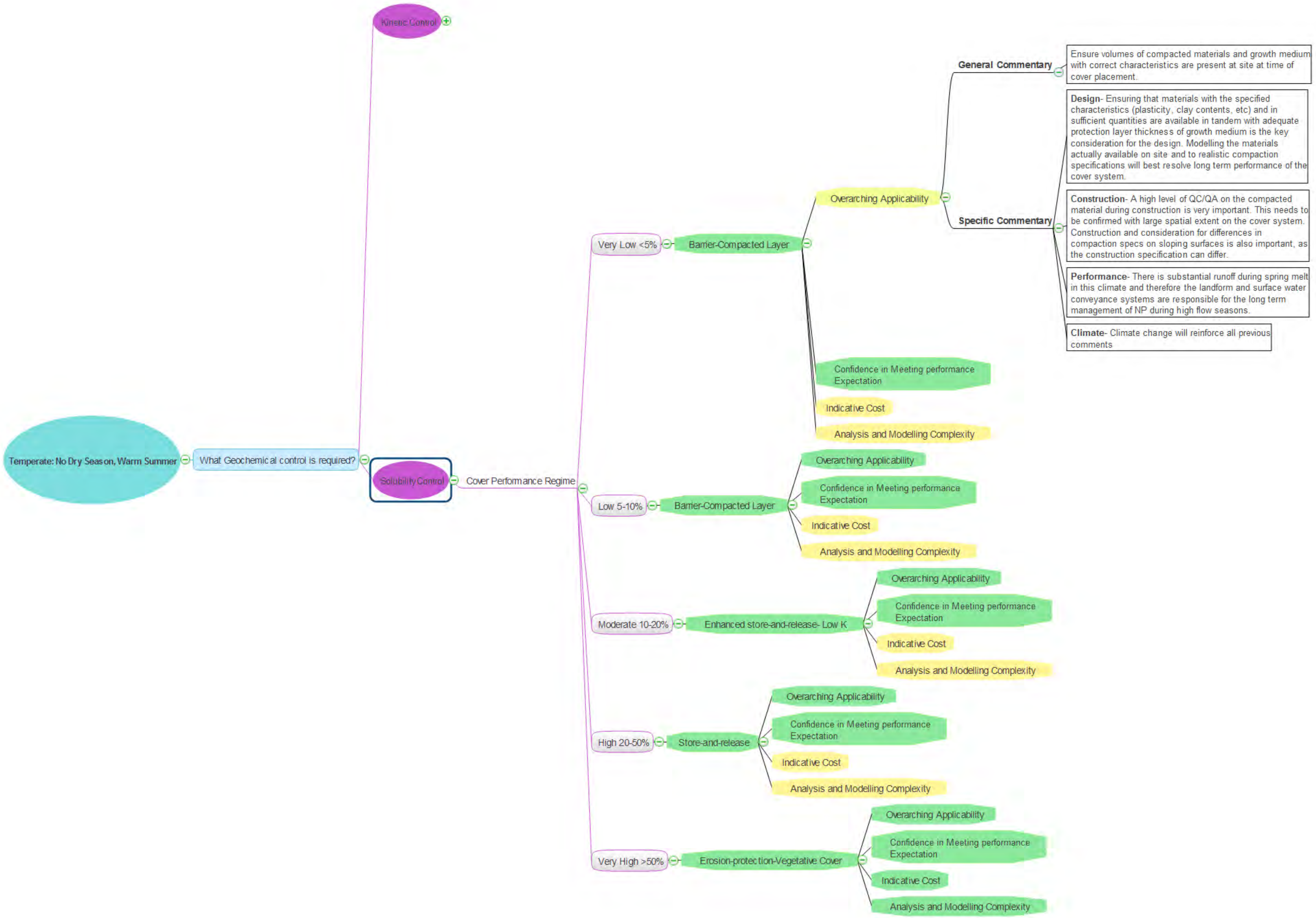
Design- There is enough precipitation supplied to be coupled with a soil based cover system design alternative. Key is maintaining moisture content of the low permeability layer. Overlying growth medium must therefore be able to supply adequate water to vegetation to prevent plants from accessing moisture from barrier layer. Care needs to be taken to ensure growth medium does not drop below wilting point for extended periods of time. Vegetation may root deeper in search for deeper stored water in the barrier layer.

Construction- high level of QA/QC on CCL construction and consideration for differences in compaction specs on sloping surfaces. Ensure no segregation occurs in overlying growth medium materials which could lead to preferential flow. Growth Medium thickness specification also important to ensure desiccation of the barrier layer does not occur.

Performance- If the adequate materials for this cover system alternative are available, climate will supply adequate water to maintain high degrees of saturation. Performance will therefore rely on the ability of the design to maintain those nearly saturated conditions throughout the year.The most susceptible period for oxygen ingress will be in the summer periods where AET rates are high, depleting cover of stored water. Modeling complexity difficult, because vegetation demands on water need to be quantified for climax condition and for dry years to understand if air permeability can be kept low.

Climate- Based on geographical constraints to this climate type, climate change is not expected to shift current climate regime significantly.

3.10 Temperate: No Dry Season, Warm Summer (NP)



Ensure volumes of compacted materials and growth medium with correct characteristics are present at site at time of cover placement.

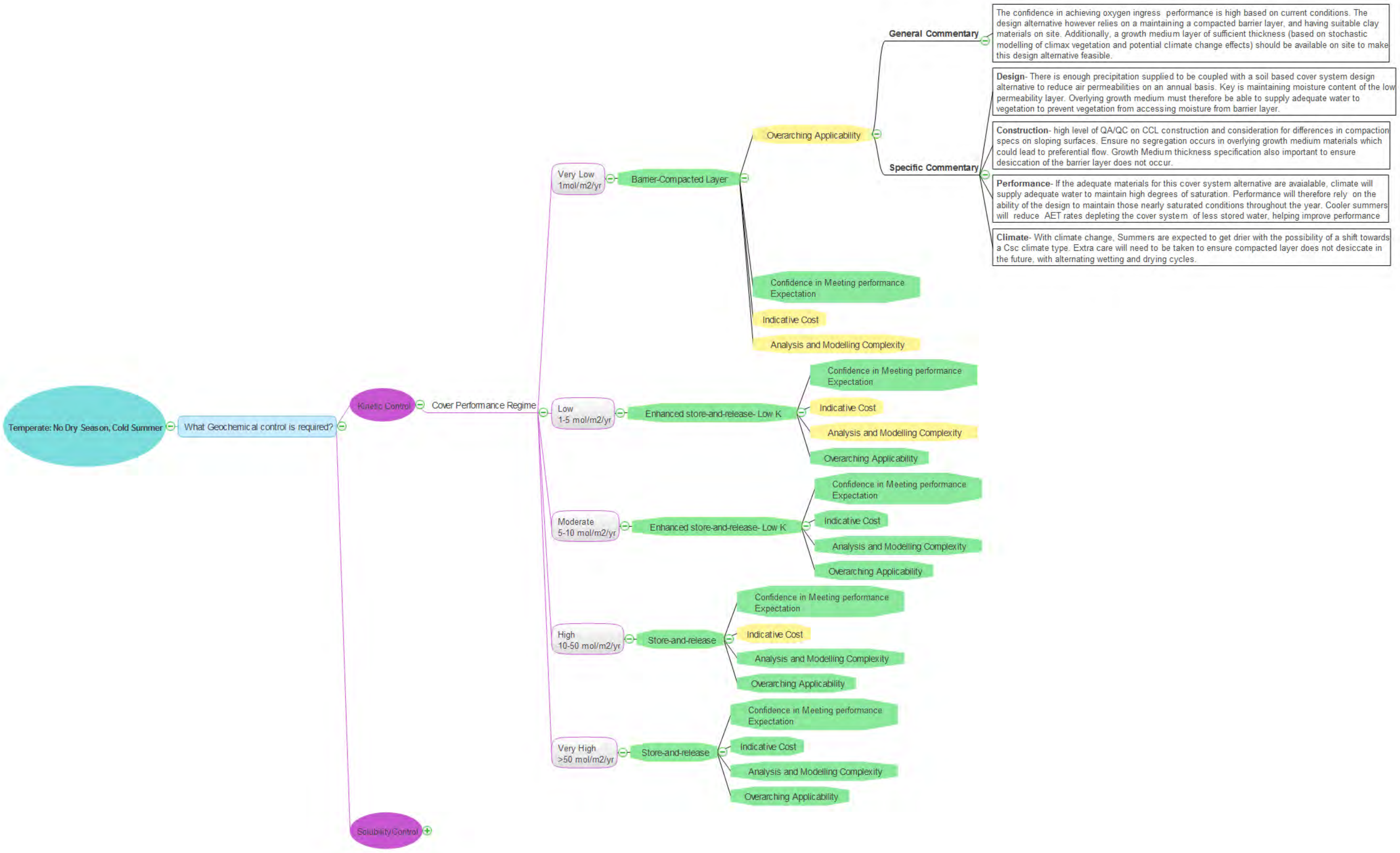
Design- Ensuring that materials with the specified characteristics (plasticity, clay contents, etc) and in sufficient quantities are available in tandem with adequate protection layer thickness of growth medium is the key consideration for the design. Modelling the materials actually available on site and to realistic compaction specifications will best resolve long term performance of the cover system.

Construction- A high level of QC/QA on the compacted material during construction is very important. This needs to be confirmed with large spatial extent on the cover system. Construction and consideration for differences in compaction specs on sloping surfaces is also important, as the construction specification can differ.

Performance- There is substantial runoff during spring melt in this climate and therefore the landform and surface water conveyance systems are responsible for the long term management of NP during high flow seasons.

Climate- Climate change will reinforce all previous comments

3.11 Temperate: No Dry Season, Cold Summer (O_2)



The confidence in achieving oxygen ingress performance is high based on current conditions. The design alternative however relies on a maintaining a compacted barrier layer, and having suitable clay materials on site. Additionally, a growth medium layer of sufficient thickness (based on stochastic modelling of climax vegetation and potential climate change effects) should be available on site to make this design alternative feasible.

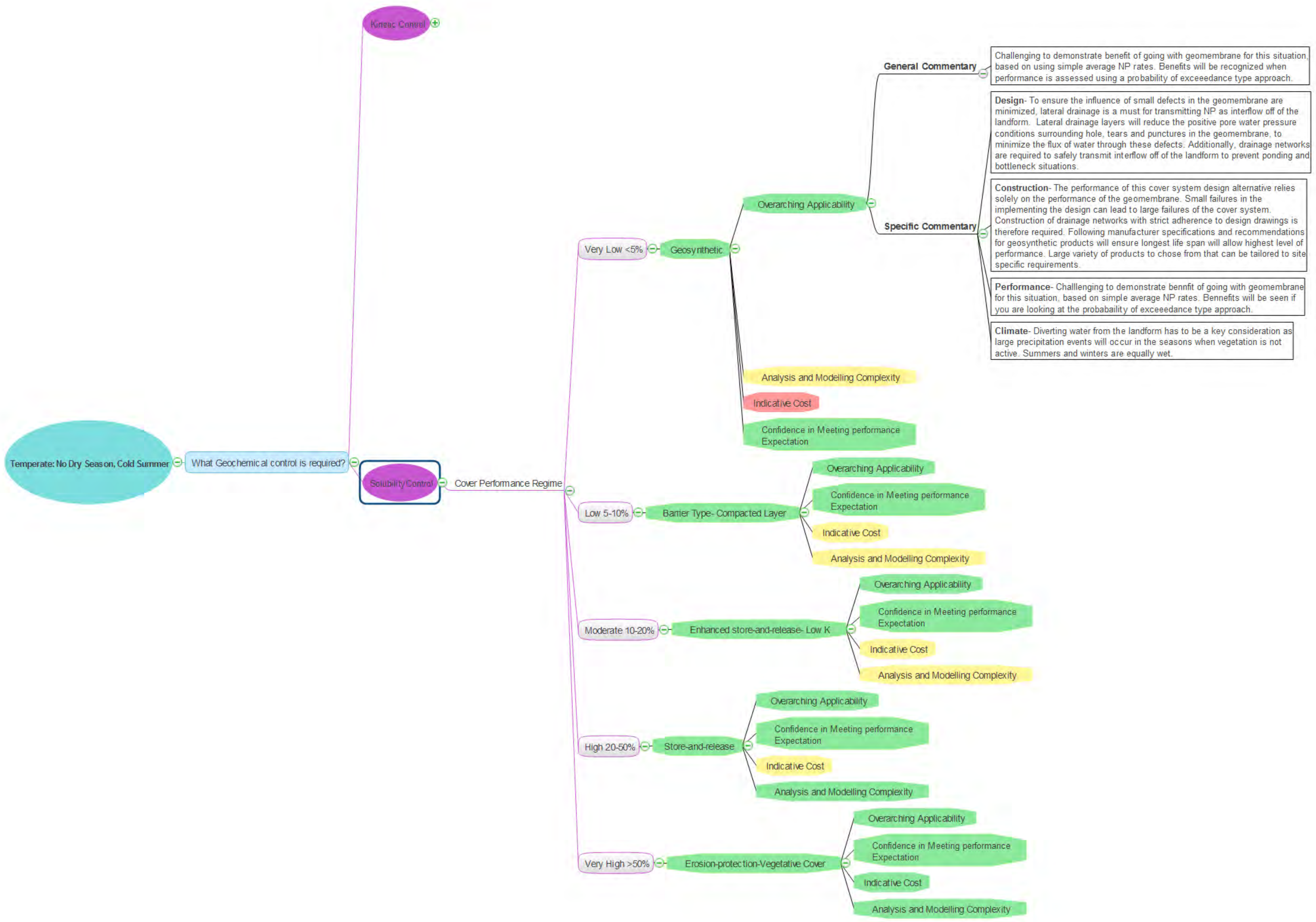
Design- There is enough precipitation supplied to be coupled with a soil based cover system design alternative to reduce air permeabilities on an annual basis. Key is maintaining moisture content of the low permeability layer. Overlying growth medium must therefore be able to supply adequate water to vegetation to prevent vegetation from accessing moisture from barrier layer.

Construction- high level of QA/QC on CCL construction and consideration for differences in compaction specs on sloping surfaces. Ensure no segregation occurs in overlying growth medium materials which could lead to preferential flow. Growth Medium thickness specification also important to ensure desiccation of the barrier layer does not occur.

Performance- If the adequate materials for this cover system alternative are avaialable, climate will supply adequate water to maintain high degrees of saturation. Performance will therefore rely on the ability of the design to maintain those nearly saturated conditions throughout the year. Cooler summers will reduce AET rates depleting the cover system of less stored water, helping improve performance

Climate- With climate change, Summers are expected to get drier with the possibility of a shift towards a Csc climate type. Extra care will need to be taken to ensure compacted layer does not desiccate in the future, with alternating wetting and drying cycles.

3.12 Temperate: No Dry Season, Cold Summer (NP)



Challenging to demonstrate benefit of going with geomembrane for this situation, based on using simple average NP rates. Benefits will be recognized when performance is assessed using a probability of exceeedance type approach.

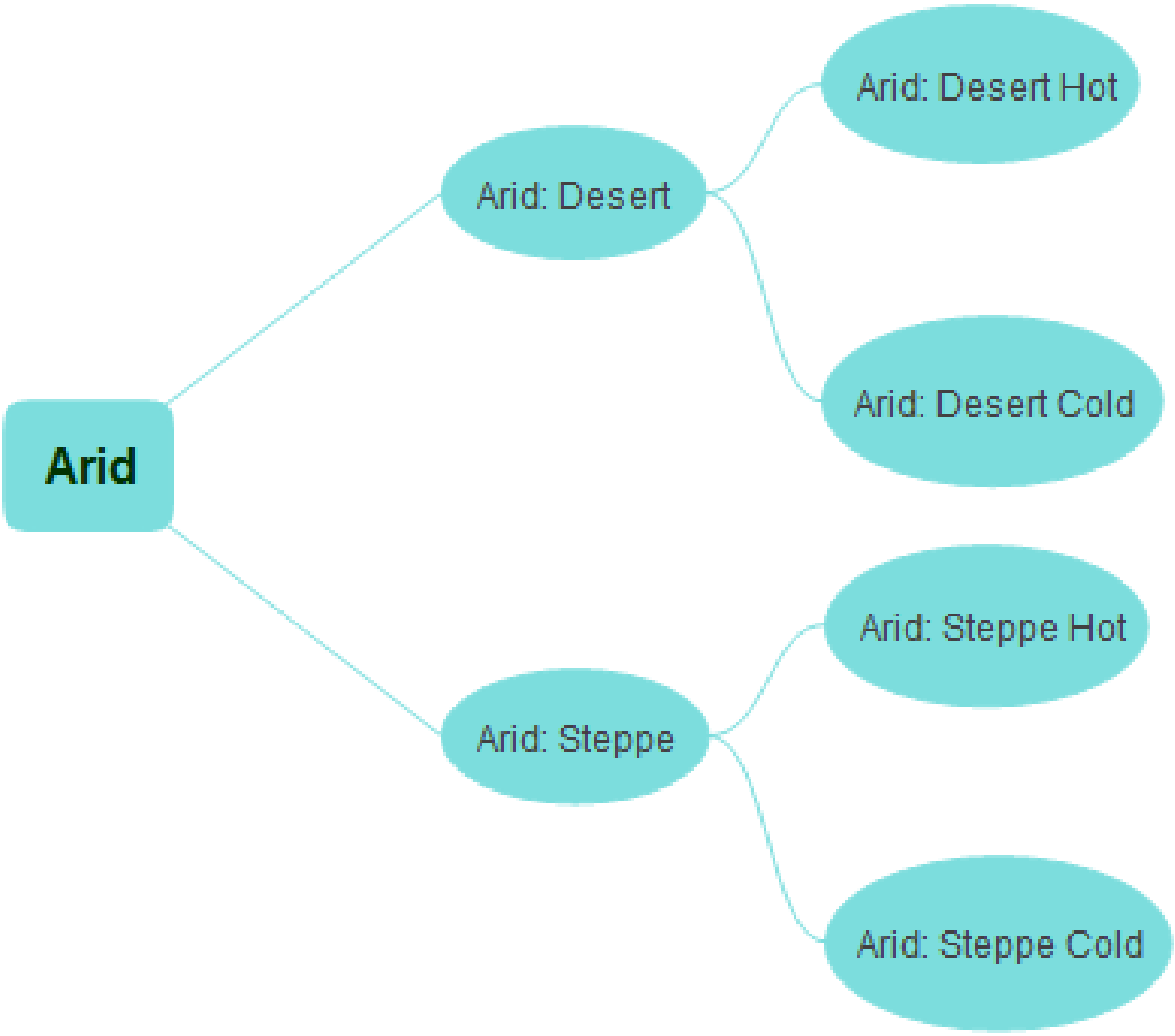
Design- To ensure the influence of small defects in the geomembrane are minimized, lateral drainage is a must for transmitting NP as interflow off of the landform. Lateral drainage layers will reduce the positive pore water pressure conditions surrounding hole, tears and punctures in the geomembrane, to minimize the flux of water through these defects. Additionally, drainage networks are required to safely transmit interflow off of the landform to prevent ponding and bottleneck situations.

Construction- The performance of this cover system design alternative relies solely on the performance of the geomembrane. Small failures in the implementing the design can lead to large failures of the cover system. Construction of drainage networks with strict adherence to design drawings is therefore required. Following manufacturer specifications and recommendations for geosynthetic products will ensure longest life span will allow highest level of performance. Large variety of products to chose from that can be tailored to site specific requirements.

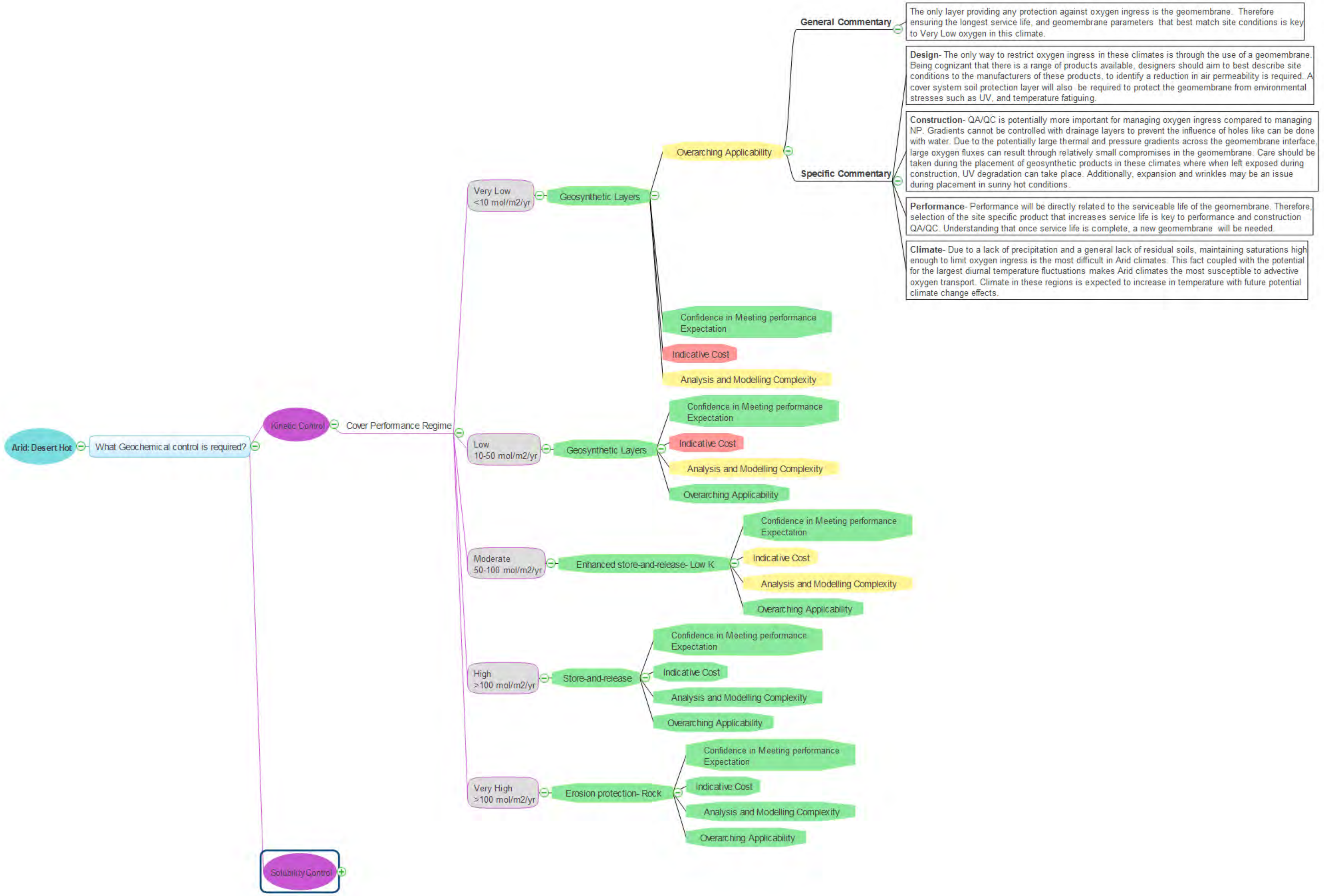
Performance- Challlenging to demonstrate bennfit of going with geomembrane for this situation, based on simple average NP rates. Bennefits will be seen if you are looking at the probabaility of exceeedance type approach.

Climate- Diverting water from the landform has to be a key consideration as large precipitation events will occur in the seasons when vegetation is not active. Summers and winters are equally wet.

4 ARID CLIMATE OVERVIEW



4.1 Arid: Desert, Hot (O_2)



The only layer providing any protection against oxygen ingress is the geomembrane. Therefore ensuring the longest service life, and geomembrane parameters that best match site conditions is key to Very Low oxygen in this climate.

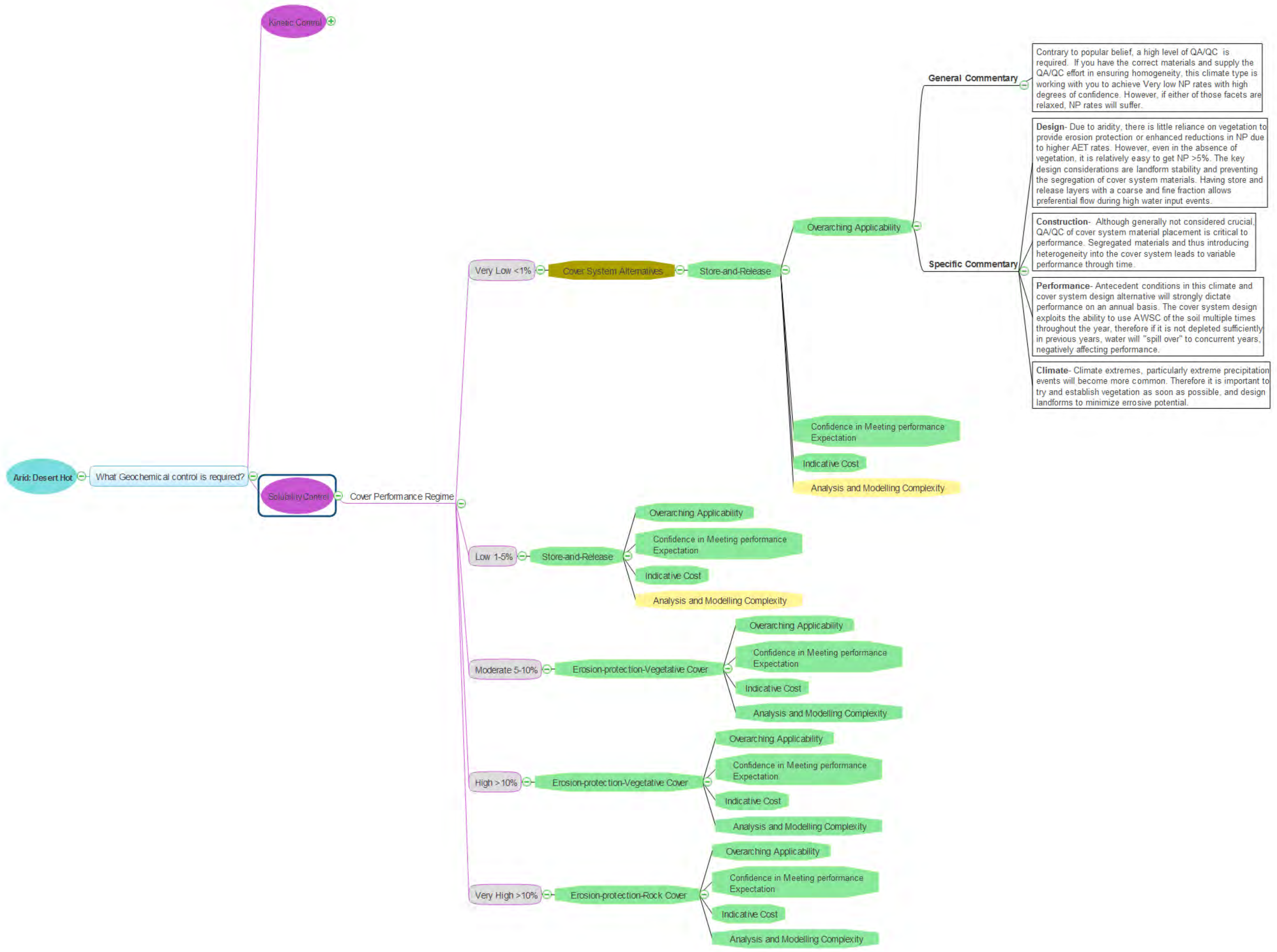
Design- The only way to restrict oxygen ingress in these climates is through the use of a geomembrane. Being cognizant that there is a range of products available, designers should aim to best describe site conditions to the manufacturers of these products, to identify a reduction in air permeability is required. A cover system soil protection layer will also be required to protect the geomembrane from environmental stresses such as UV, and temperature fatiguing.

Construction- QA/QC is potentially more important for managing oxygen ingress compared to managing NP. Gradients cannot be controlled with drainage layers to prevent the influence of holes like can be done with water. Due to the potentially large thermal and pressure gradients across the geomembrane interface, large oxygen fluxes can result through relatively small compromises in the geomembrane. Care should be taken during the placement of geosynthetic products in these climates where when left exposed during construction, UV degradation can take place. Additionally, expansion and wrinkles may be an issue during placement in sunny hot conditions.

Performance- Performance will be directly related to the serviceable life of the geomembrane. Therefore, selection of the site specific product that increases service life is key to performance and construction QA/QC. Understanding that once service life is complete, a new geomembrane will be needed.

Climate- Due to a lack of precipitation and a general lack of residual soils, maintaining saturations high enough to limit oxygen ingress is the most difficult in Arid climates. This fact coupled with the potential for the largest diurnal temperature fluctuations makes Arid climates the most susceptible to advective oxygen transport. Climate in these regions is expected to increase in temperature with future potential climate change effects.

4.2 Arid: Desert, Hot (NP)



Contrary to popular belief, a high level of QA/QC is required. If you have the correct materials and supply the QA/QC effort in ensuring homogeneity, this climate type is working with you to achieve Very low NP rates with high degrees of confidence. However, if either of those facets are relaxed, NP rates will suffer.

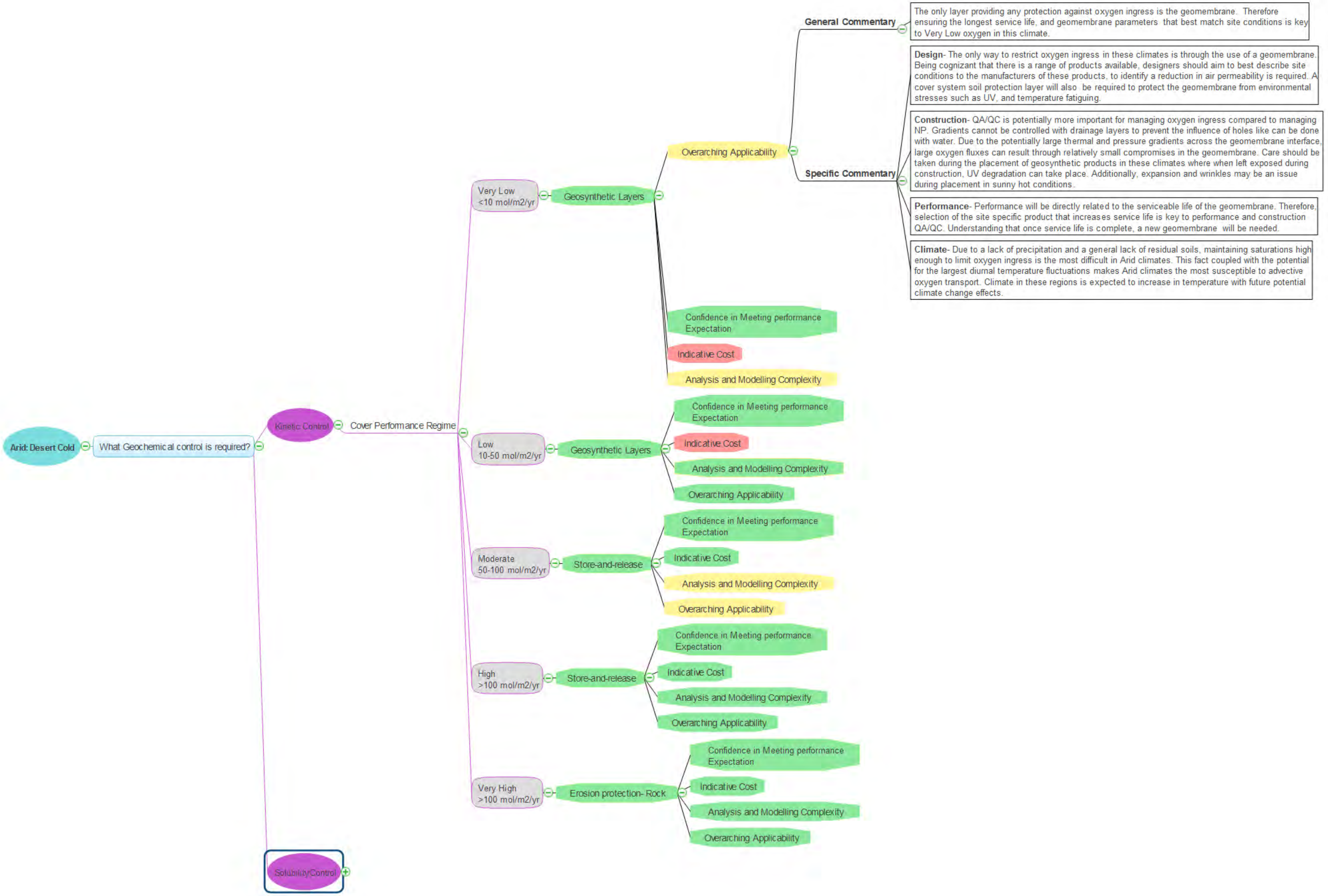
Design- Due to aridity, there is little reliance on vegetation to provide erosion protection or enhanced reductions in NP due to higher AET rates. However, even in the absence of vegetation, it is relatively easy to get NP >5%. The key design considerations are landform stability and preventing the segregation of cover system materials. Having store and release layers with a coarse and fine fraction allows preferential flow during high water input events.

Construction- Although generally not considered crucial, QA/QC of cover system material placement is critical to performance. Segregated materials and thus introducing heterogeneity into the cover system leads to variable performance through time.

Performance- Antecedent conditions in this climate and cover system design alternative will strongly dictate performance on an annual basis. The cover system design exploits the ability to use AWSC of the soil multiple times throughout the year, therefore if it is not depleted sufficiently in previous years, water will "spill over" to concurrent years, negatively affecting performance.

Climate- Climate extremes, particularly extreme precipitation events will become more common. Therefore it is important to try and establish vegetation as soon as possible, and design landforms to minimize errosive potential.

4.3 Arid: Desert, Cold (O_2)



The only layer providing any protection against oxygen ingress is the geomembrane. Therefore ensuring the longest service life, and geomembrane parameters that best match site conditions is key to Very Low oxygen in this climate.

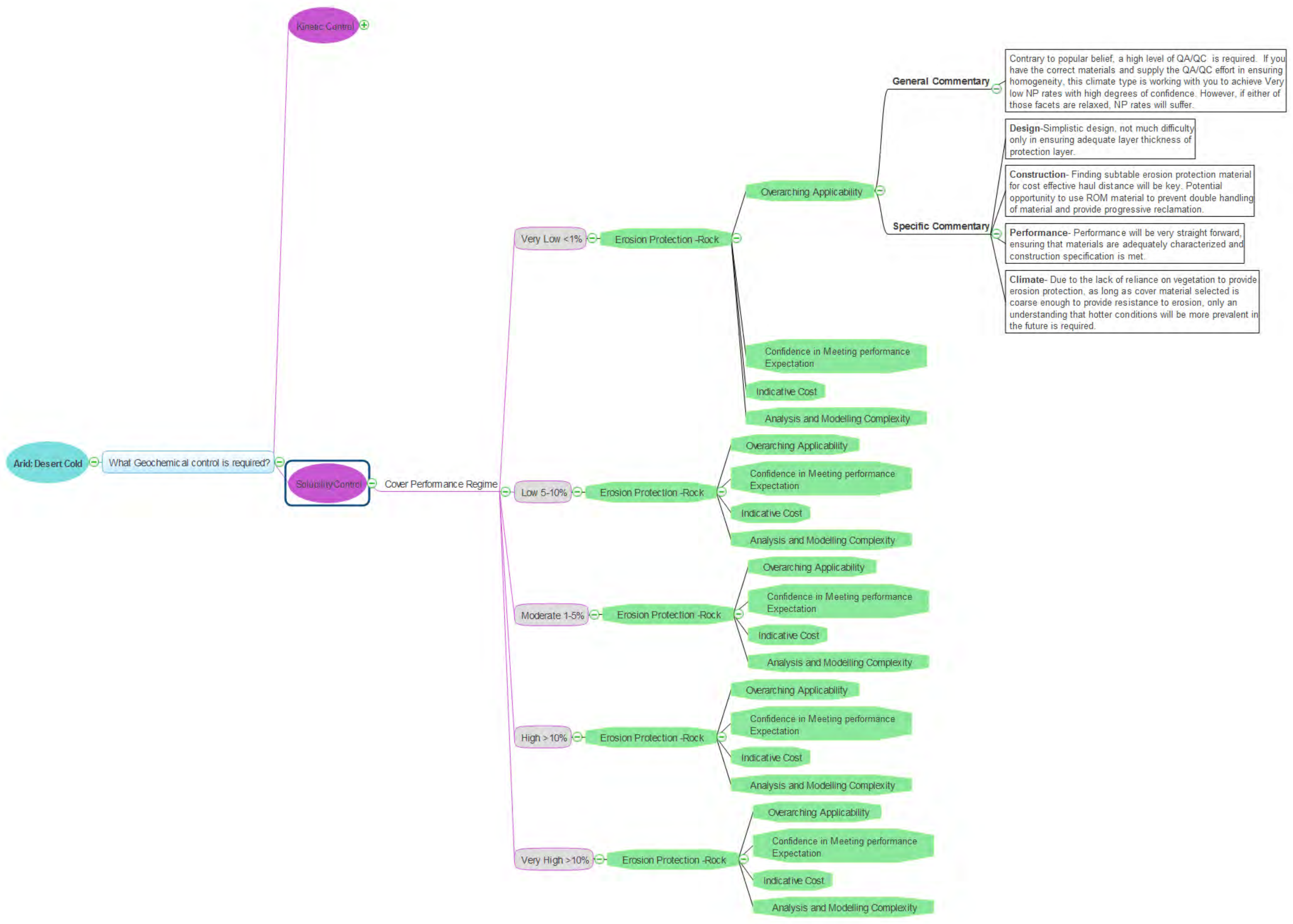
Design- The only way to restrict oxygen ingress in these climates is through the use of a geomembrane. Being cognizant that there is a range of products available, designers should aim to best describe site conditions to the manufacturers of these products, to identify a reduction in air permeability is required. A cover system soil protection layer will also be required to protect the geomembrane from environmental stresses such as UV, and temperature fatiguing.

Construction- QA/QC is potentially more important for managing oxygen ingress compared to managing NP. Gradients cannot be controlled with drainage layers to prevent the influence of holes like can be done with water. Due to the potentially large thermal and pressure gradients across the geomembrane interface, large oxygen fluxes can result through relatively small compromises in the geomembrane. Care should be taken during the placement of geosynthetic products in these climates where when left exposed during construction, UV degradation can take place. Additionally, expansion and wrinkles may be an issue during placement in sunny hot conditions.

Performance- Performance will be directly related to the serviceable life of the geomembrane. Therefore, selection of the site specific product that increases service life is key to performance and construction QA/QC. Understanding that once service life is complete, a new geomembrane will be needed.

Climate- Due to a lack of precipitation and a general lack of residual soils, maintaining saturations high enough to limit oxygen ingress is the most difficult in Arid climates. This fact coupled with the potential for the largest diurnal temperature fluctuations makes Arid climates the most susceptible to advective oxygen transport. Climate in these regions is expected to increase in temperature with future potential climate change effects.

4.4 Arid: Desert, Cold (NP)



Contrary to popular belief, a high level of QA/QC is required. If you have the correct materials and supply the QA/QC effort in ensuring homogeneity, this climate type is working with you to achieve Very low NP rates with high degrees of confidence. However, if either of those facets are relaxed, NP rates will suffer.

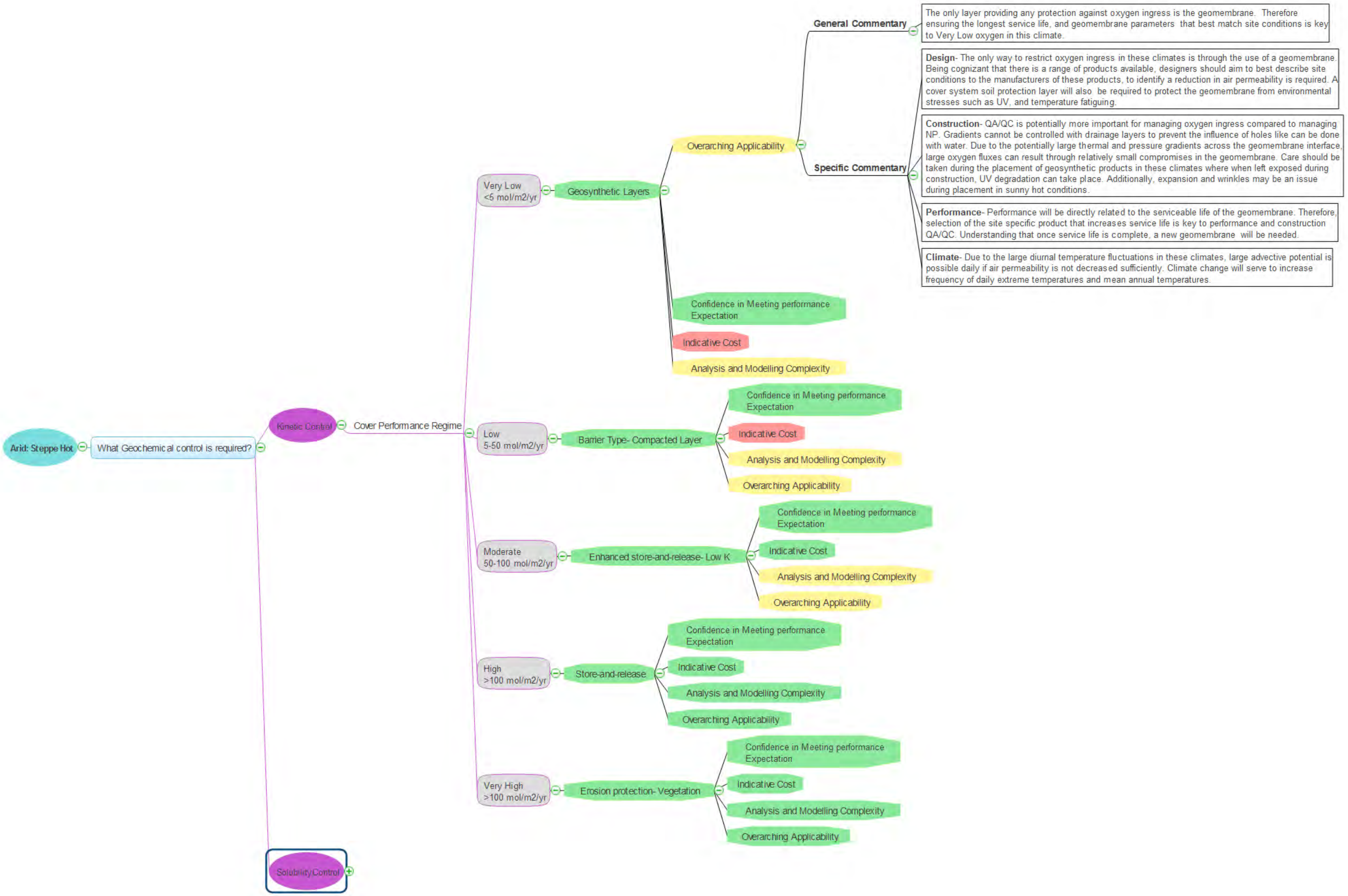
Design-Simplistic design, not much difficulty only in ensuring adequate layer thickness of protection layer.

Construction- Finding subtable erosion protection material for cost effective haul distance will be key. Potential opportunity to use ROM material to prevent double handling of material and provide progressive reclamation.

Performance- Performance will be very straight forward, ensuring that materials are adequately characterized and construction specification is met.

Climate- Due to the lack of reliance on vegetation to provide erosion protection, as long as cover material selected is coarse enough to provide resistance to erosion, only an understanding that hotter conditions will be more prevalent in the future is required.

4.5 Arid: Steppe, Hot (O_2)



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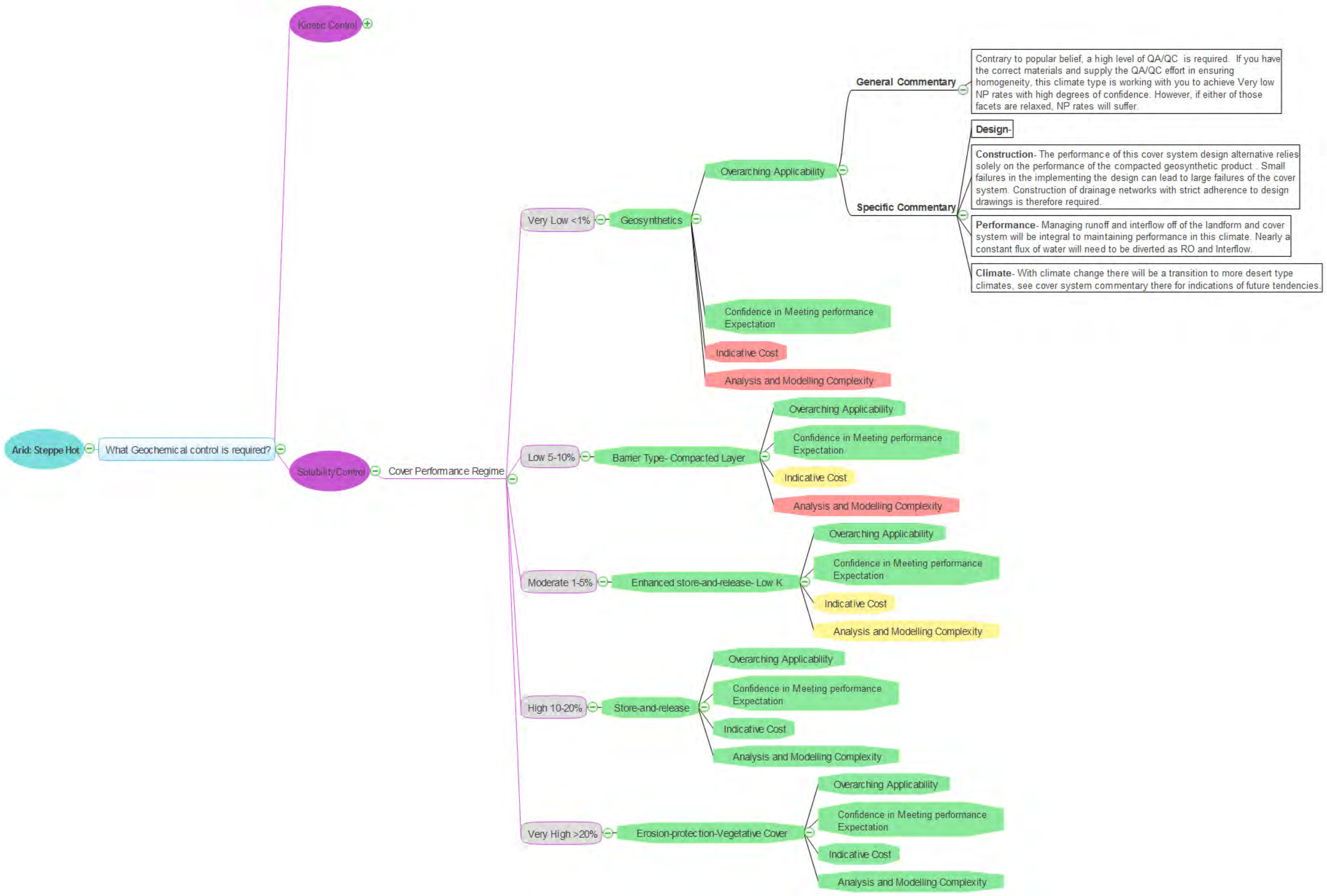
Design- The only way to restrict oxygen ingress in these climates is through the use of a geomembrane. Being cognizant that there is a range of products available, designers should aim to best describe site conditions to the manufacturers of these products, to identify a reduction in air permeability is required. A cover system soil protection layer will also be required to protect the geomembrane from environmental stresses such as UV, and temperature fatiguing.

Construction- QA/QC is potentially more important for managing oxygen ingress compared to managing NP. Gradients cannot be controlled with drainage layers to prevent the influence of holes like can be done with water. Due to the potentially large thermal and pressure gradients across the geomembrane interface, large oxygen fluxes can result through relatively small compromises in the geomembrane. Care should be taken during the placement of geosynthetic products in these climates where when left exposed during construction, UV degradation can take place. Additionally, expansion and wrinkles may be an issue during placement in sunny hot conditions.

Performance- Performance will be directly related to the serviceable life of the geomembrane. Therefore, selection of the site specific product that increases service life is key to performance and construction QA/QC. Understanding that once service life is complete, a new geomembrane will be needed.

Climate- Due to the large diurnal temperature fluctuations in these climates, large advective potential is possible daily if air permeability is not decreased sufficiently. Climate change will serve to increase frequency of daily extreme temperatures and mean annual temperatures.

4.6 Arid: Steppe, Hot (NP)



Contrary to popular belief, a high level of QA/QC is required. If you have the correct materials and supply the QA/QC effort in ensuring homogeneity, this climate type is working with you to achieve Very low NP rates with high degrees of confidence. However, if either of those facets are relaxed, NP rates will suffer.

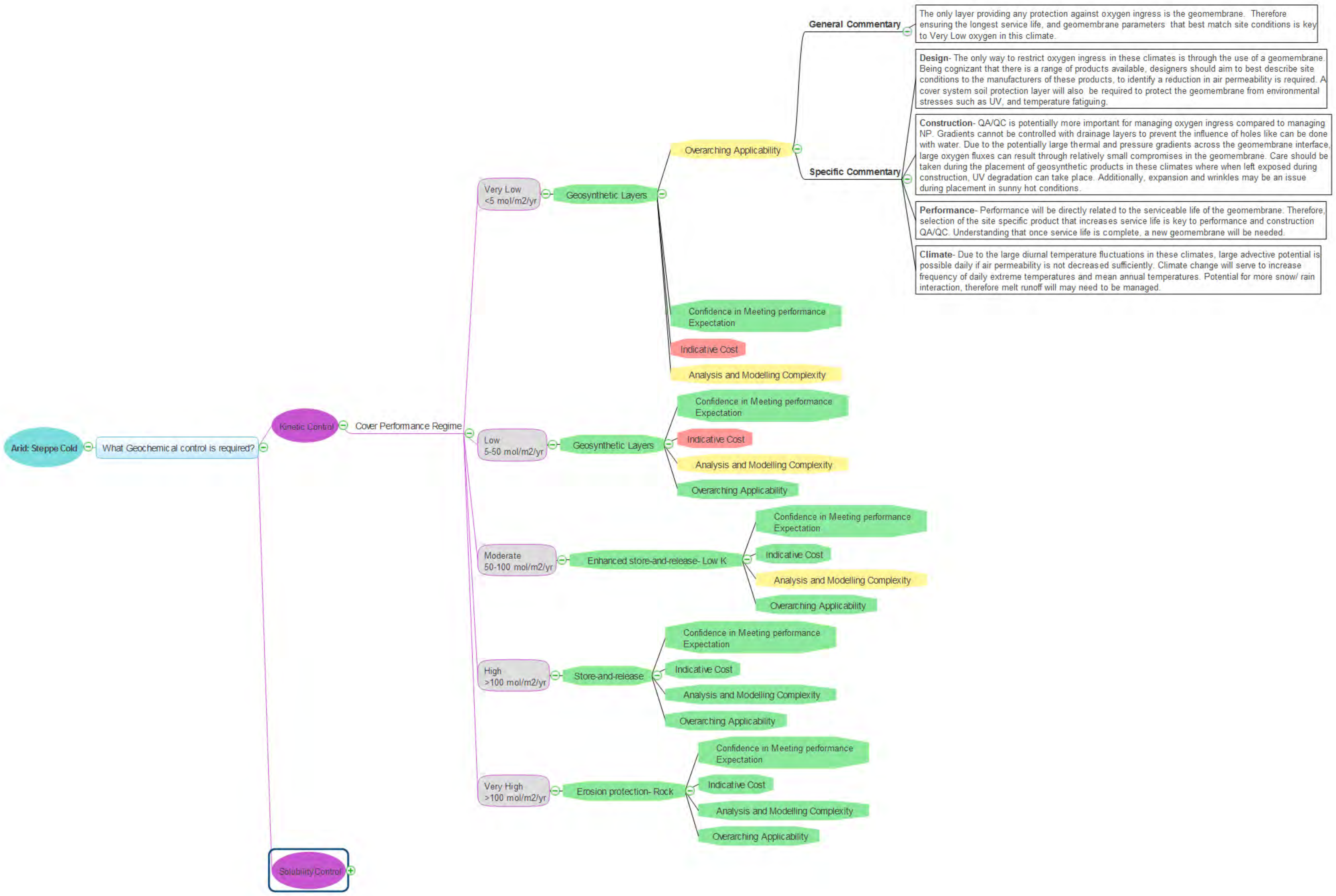
Design-

Construction- The performance of this cover system design alternative relies solely on the performance of the compacted geosynthetic product . Small failures in the implementing the design can lead to large failures of the cover system. Construction of drainage networks with strict adherence to design drawings is therefore required.

Performance- Managing runoff and interflow off of the landform and cover system will be integral to maintaining performance in this climate. Nearly a constant flux of water will need to be diverted as RO and Interflow.

Climate- With climate change there will be a transition to more desert type climates, see cover system commentary there for indications of future tendencies.

4.7 Arid: Steppe, Cold (O_2)



The only layer providing any protection against oxygen ingress is the geomembrane. Therefore ensuring the longest service life, and geomembrane parameters that best match site conditions is key to Very Low oxygen in this climate.

Design- The only way to restrict oxygen ingress in these climates is through the use of a geomembrane. Being cognizant that there is a range of products available, designers should aim to best describe site conditions to the manufacturers of these products, to identify a reduction in air permeability is required. A cover system soil protection layer will also be required to protect the geomembrane from environmental stresses such as UV, and temperature fatiguing.

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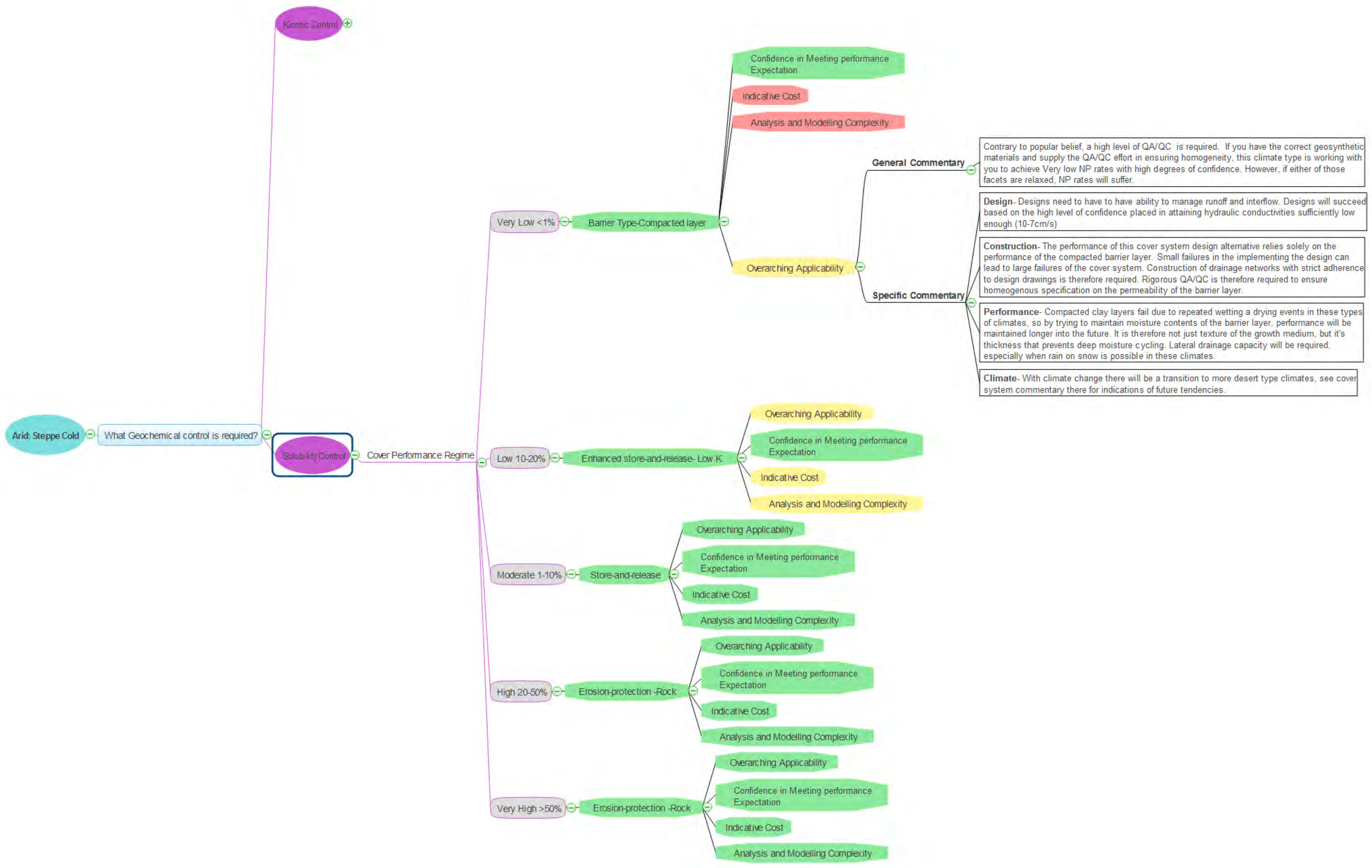
Performance- Performance will be directly related to the serviceable life of the geomembrane. Therefore, selection of the site specific product that increases service life is key to performance and construction QA/QC. Understanding that once service life is complete, a new geomembrane will be needed.

Climate- Due to the large diurnal temperature fluctuations in these climates, large advective potential is possible daily if air permeability is not decreased sufficiently. Climate change will serve to increase frequency of daily extreme temperatures and mean annual temperatures. Potential for more snow/ rain interaction, therefore melt runoff will may need to be managed.

4.8 Arid: Steppe, Cold (NP)



Contrary to popular belief, a high level of QA/QC is required. If you have the correct geosynthetic materials and supply the QA/QC effort in ensuring homogeneity, this climate type is working with you to achieve Very low NP rates with high degrees of confidence. However, if either of those facets are relaxed, NP rates will suffer.

Design- Designs need to have to have ability to manage runoff and interflow. Designs will succeed based on the high level of confidence placed in attaining hydraulic conductivities sufficiently low enough (10-7cm/s)

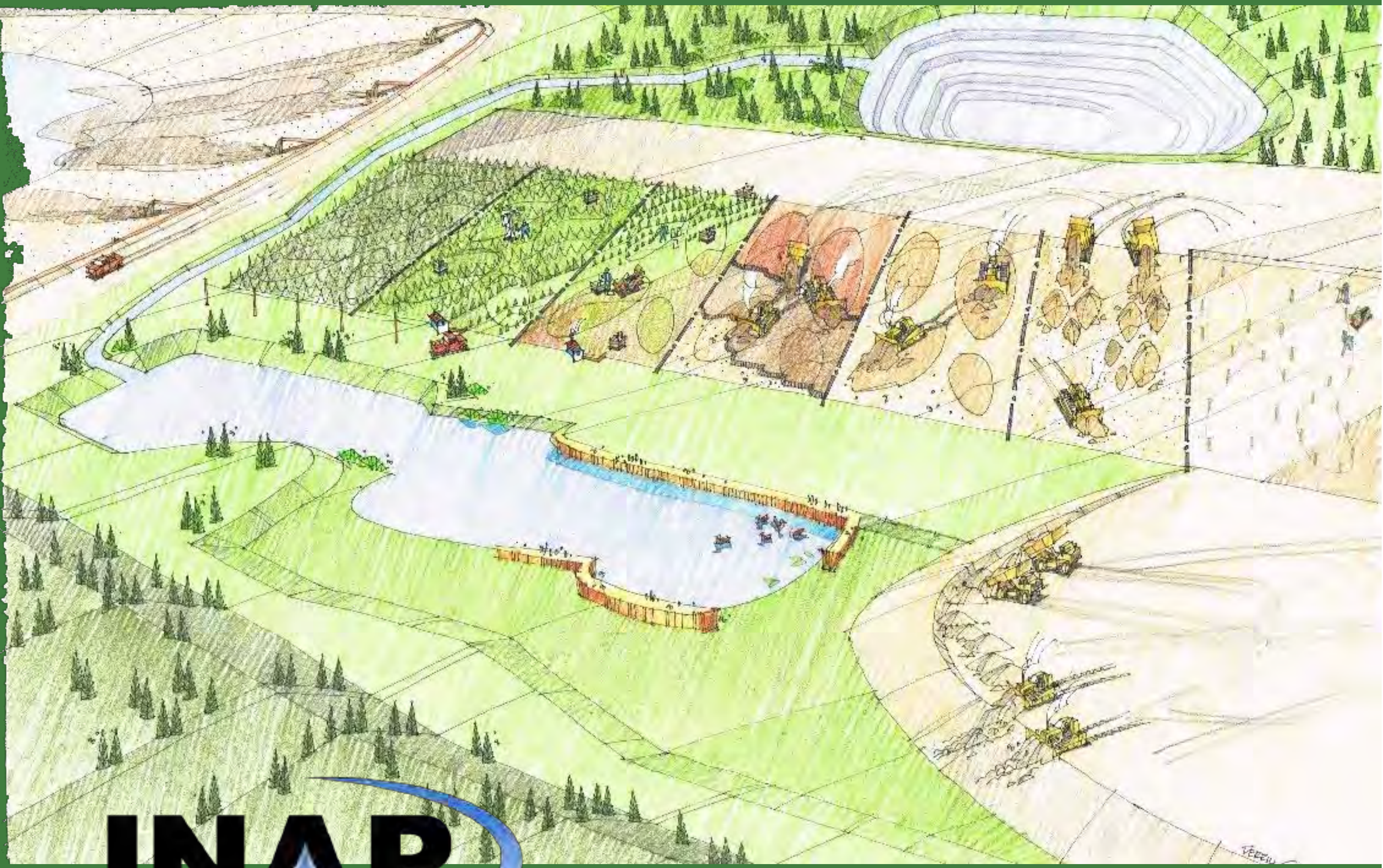
Construction- The performance of this cover system design alternative relies solely on the performance of the compacted barrier layer. Small failures in the implementing the design can lead to large failures of the cover system. Construction of drainage networks with strict adherence to design drawings is therefore required. Rigorous QA/QC is therefore required to ensure homeogenous specification on the permeability of the barrier layer.

Performance- Compacted clay layers fail due to repeated wetting a drying events in these types of climates, so by trying to maintain moisture contents of the barrier layer, performance will be maintained longer into the future. It is therefore not just texture of the growth medium, but it's thickness that prevents deep moisture cycling. Lateral drainage capacity will be required, especially when rain on snow is possible in these climates.

Climate- With climate change there will be a transition to more desert type climates, see cover system commentary there for indications of future tendencies.

GLOBAL COVER SYSTEM DESIGN

APPENDIX B: MATERIALS



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B1. AVAILABILITY OF COVER MATERIALS

One of the six key lessons learned in this document speaks to the availability, or scarcity, of cover materials, as well as haul distances from borrow sources. This is a key factor in developing cover system designs, which is often overlooked at the conceptual design stage and then leads to increasing costs when moving to detailed design.

Transport and placement costs are evaluated against the benefits of utilizing greater volumes and/or more desirable materials. Licensing may also be required to access/use borrow materials, adding substantial, perhaps prohibitive, costs and time to the process. For example, a third party may require that an airstrip at a remote site be left untouched to allow for future land uses (e.g., recreation use; hunting, fishing, etc.). However, the material within the airstrip may represent a cost-effective borrow area for cover system construction.

Scarcity of natural materials often goes hand in hand with increasing variability of material properties. Adequate geochemical and geotechnical characterization of borrow material sources is especially important as material variability increases. Predictions of cover system performance must account for this variability.

Borrow area management must be fully addressed. This should include: access, slope stability and water management (operation and post-closure), management of reject materials, and reclamation. Ideally, borrow can come from within the mining or dump footprints, salvaged and placed directly, or stockpiled during mining. Next best is on-site borrow, and least favourable is off-site borrow. In cold regions, disturbing land for borrow can lead to permanent permafrost loss, making good borrow-pit reclamation very challenging. As in dam design, borrow-source identification, characterization, delineation, and access are important, but often neglected, aspects of cover system design.

B2. SOIL SALVAGE

Soil is the upper, biogeochemically weathered layers of unconsolidated surficial material. It differs from underlying layers in having higher organic matter content, more numerous and diverse biota, including vegetation propagules, and in having been altered from parent-material properties through weathering processes (Brady, 1990). Conventionally, mine operations have considered soil salvage, storage, and use only where the soil is overburden that must be removed for pit development, or where its removal is otherwise required for geotechnical reasons (e.g., within the footprint of a waste rock dump). Other soils within the mine footprint are frequently buried under waste rock and tailings deposits, due to the substantial costs of salvaging these soil materials. However, soils constitute a reclamation and closure resource, which typically has substantial nutritional, physical (finer particle size distributions), and biological benefits for incorporation in cover system growth layers. These benefits can at least partially offset recovery costs through improved performance and reductions in other closure costs, such as revegetation.

Regardless as to the argument that stockpiling topsoil material negates the biological benefits for reclamation; simply the typically finer-textured nature of this material warrants close examination as to the value of salvaging and stockpiling. Ultimately, almost every mine wishes it had stockpiled more soil for cover system construction. For these reasons, soil salvage should be optimized within all areas of the development footprint of new mine developments where salvage operations can be safely conducted.

B3. GEOCHEMICAL CHARACTERIZATION

The *GARD Guide* provides an overview of source material geochemical characterization. A phased assessment program is used to ensure adequate information is available at all stages of the project. Early recognition of the potential for acid drainage and metal leaching represents best practice for environmental management. More specifically, lack of early recognition usually results in substantive economic and environmental implications.

First, the chemistry of candidate cover materials must be considered. Cover materials with elevated levels of metals, salts, and/or other elements may produce unacceptable water quality in the receiving environment. These conditions may also be detrimental to the development of a sustainable and useful vegetation cover. Naturally mineralized elements exist in many undisturbed mining areas, and as such, elevated levels in candidate cover materials may not necessarily be cause for excluding these materials from the design. Additionally, chemical migration from underlying source material into cover material, including the growth medium, must be carefully evaluated. Initial chemical characterization may find conditions that will support vegetation. With time, however, migration of salts, metals and other elements may increase concentrations and prove detrimental to vegetation growth. An additional concern is the use of dispersive (or sodic) materials as the cover material; if not evaluated use of this type of material can lead to increased risk for erosion, and challenges with establishing sustainable vegetation.

The chemical properties of the growth medium will be an important determinant of vegetation success. Topsoil, when available, can be used as a source of nutrients and vegetation propagules, but must be protected from surface erosion through controlled surface drainage. Initial fertilizer treatments may be necessary for successful vegetation establishment, but continued applications may deter native species establishment, depending on the adaptation of the target species.

The key message is that potential cover materials be fully characterized early in the mine life, both for their potential for elevated levels of metals and salts, and as a growth media. In many cases, the site may be obliged to use some materials with less-than-ideal properties.

B4. GEOTECHNICAL CHARACTERIZATION

Characterization of a soil's physical, or geotechnical, properties is an important step in cover system design. Understanding how texture, arrangement, and placement of materials alter water and air movement helps determine the most appropriate option to limit NP, oxygen ingress, and erosion, while enhancing other reclamation objectives, such as geotechnical stability and vegetation establishment.

This section summarizes key geotechnical characteristics of cover materials. Further details are found in MEND (2011). The main parameters are texture and density, as well as hydraulic material properties (water-retention characteristics and hydraulic conductivity).

4.1 Particle Size Distribution

Material texture is generally the first component of material characterization. Particle size distribution (PSD) also gives an indication of the hydraulic conductivity and water retention properties of a candidate soil or rock material (Figure 4-1).

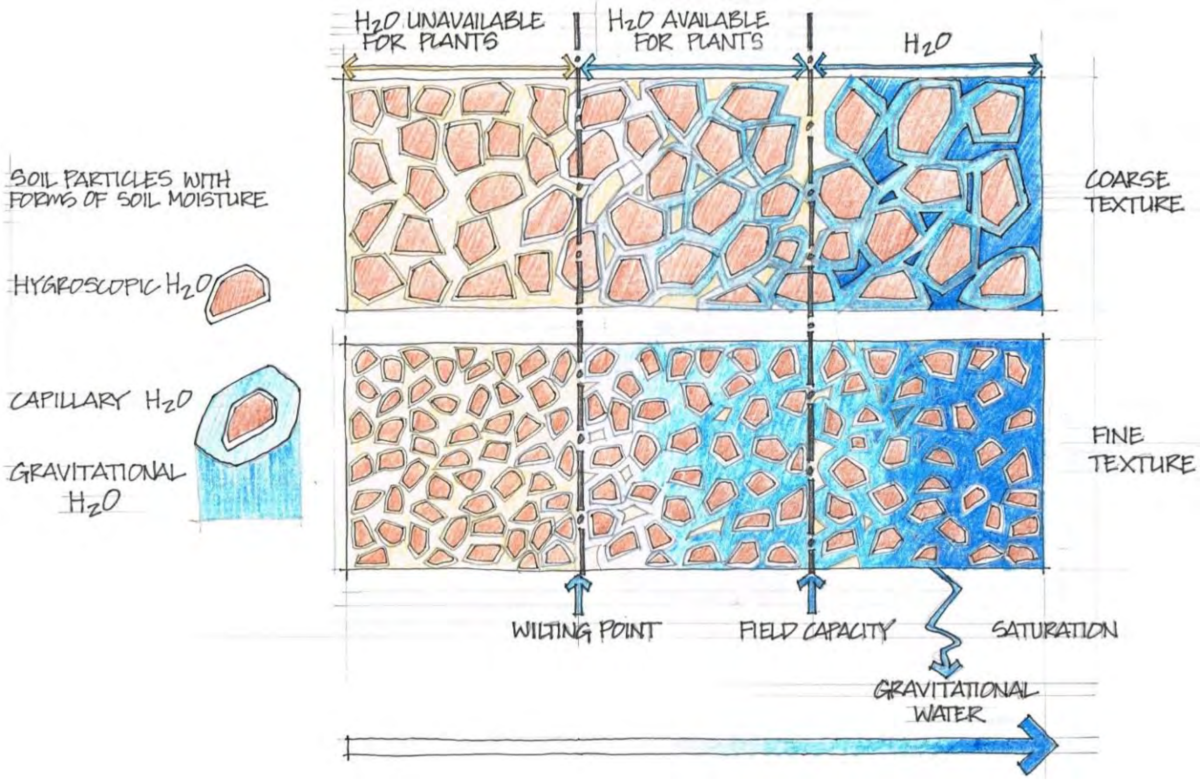


Figure 4-1. Suction-pore saturation of coarser-and finer-textured material representing field capacity.

Sieving, hydrometer, and photometric means are the most common methods of determining the range of grain sizes of available material on mine sites. Photo analysis is generally used to estimate particle size percentages too large to sieve, while hydrometers are employed for finer fractions in the range of silts and clay. PSD is often plotted on a percent passing vs. particles size semi-log graph (Figure 4-2); alternatively, ternary diagrams may be used (Figure 4-3).

An important element in material characterization is heterogeneity, and PSD testing provides an opportunity to illustrate it. Numerous samples should be characterized for PSD initially, followed by further hydraulic testing (water retention and permeability) on select samples from different textural ranges (e.g., coarser-textured and finer-textured ranges of the entire PSD envelope).

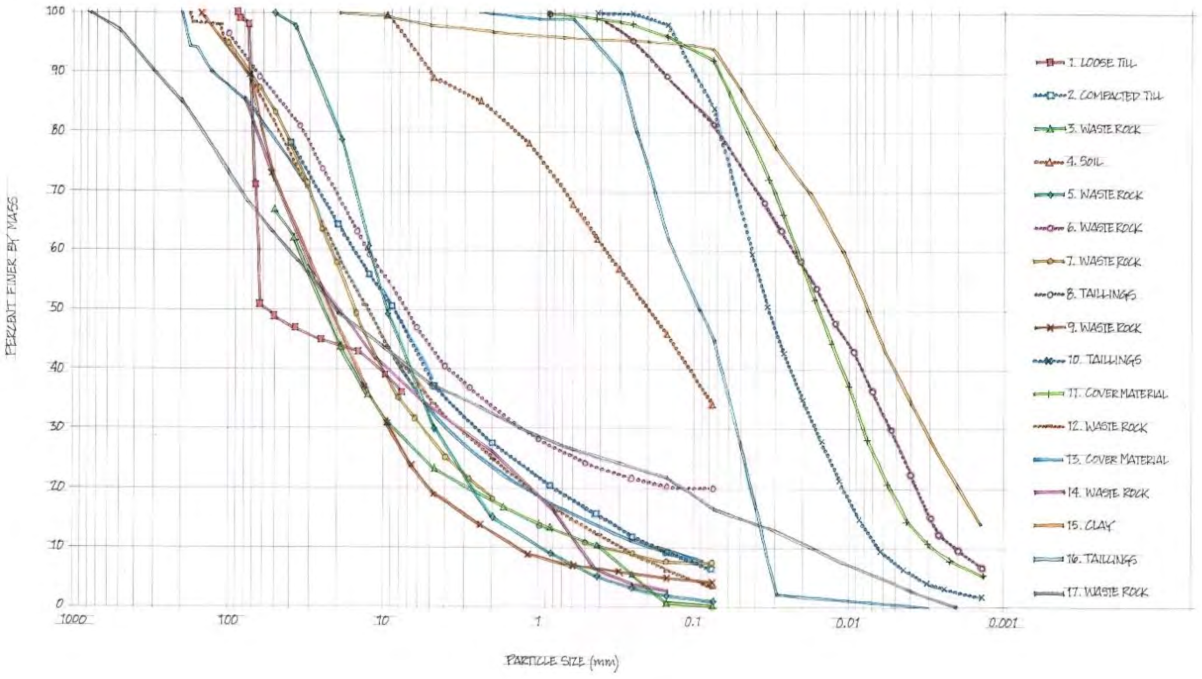


Figure 4-2. Particle size distribution for waste rock, tailings, cover materials, barrier layers and soil growth medium. 1-3 (O'Kane *et al.*, 1997), 4-5 (Reszat *et al.*, 2009), 6-7 (Shurniak *et al.*, 2009, 2012), 8-9 (Meiers *et al.*, 2009), 10-11 (Duckett and O'Kane., 2006), 12-13 (O'Kane and Waters, 2003), 14-15 (DeVos *et a*l.,1997; Ayres *et al.*, 2005), 16-17 (Brett *et al.*, 2011).

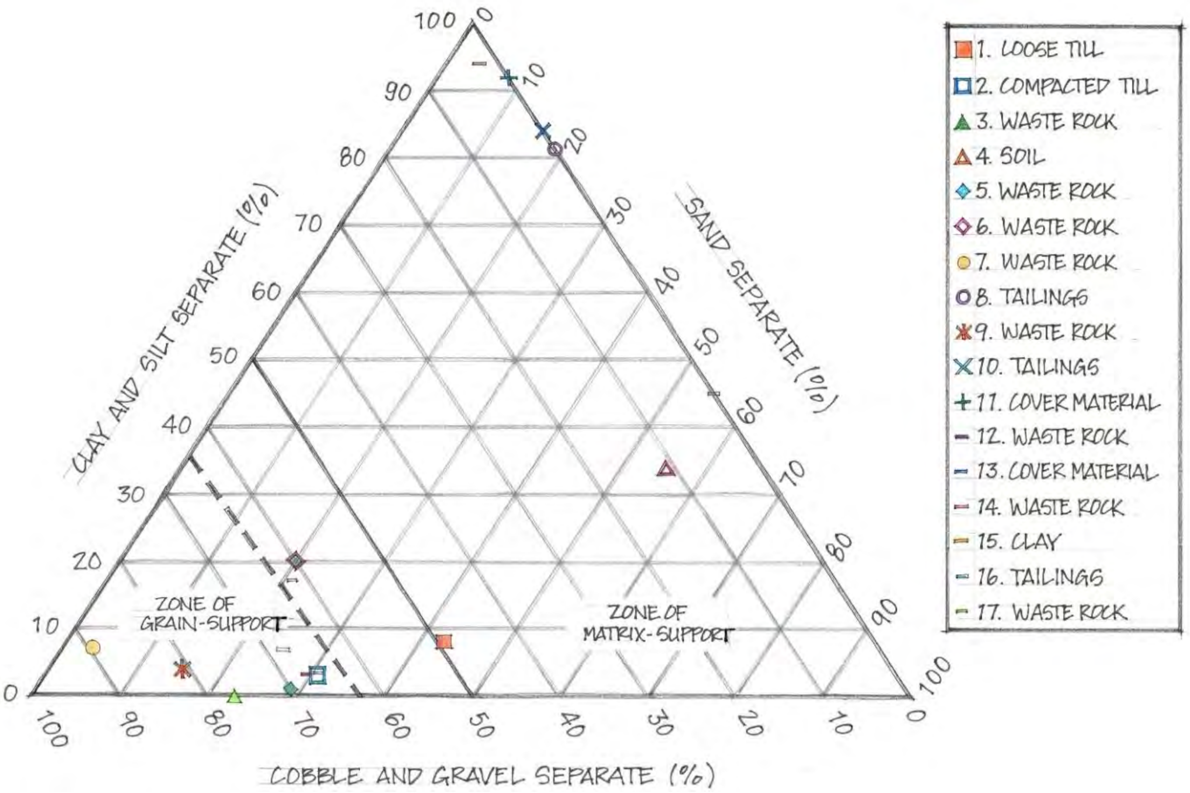


Figure 4-3. Ternary plot based on material texture with 40% passing #4 sieve plotted to separate matrix and grain supported samples (Herasymuik, 1996). 1-3 (O'Kane *et al.*, 1997), 4-5 (Reszat *et al.*, 2009), 6-7 (Shurniak *et al.*, 2009, 2012), 8-9 (Meiers *et al.*, 2009), 10-11 (Duckett and O'Kane., 2006), 12-13 (O'Kane and Waters, 2003), 14-15 (DeVos *et al.*,1997; Ayres *et al.*, 2005), 16-17 (Brett *et al.*, 2011).

4.2 Water Retention Curve

The fundamental relationship that defines the storage of water in the vadose (unsaturated) zone is the water retention curve (WRC). The WRC is central to the design of any unsaturated system, including an unsaturated cover system, because it describes the relationship between the energy state of the pore-water (matric suction or negative pore-water pressure) and the volume of water stored within the soil pores (volumetric water content) (Barbour 1998). The ability of a material to retain water under increasing negative pressures (suction) is defined by the WRC but goes by many names largely related to the discipline of use (Figure 4-4).

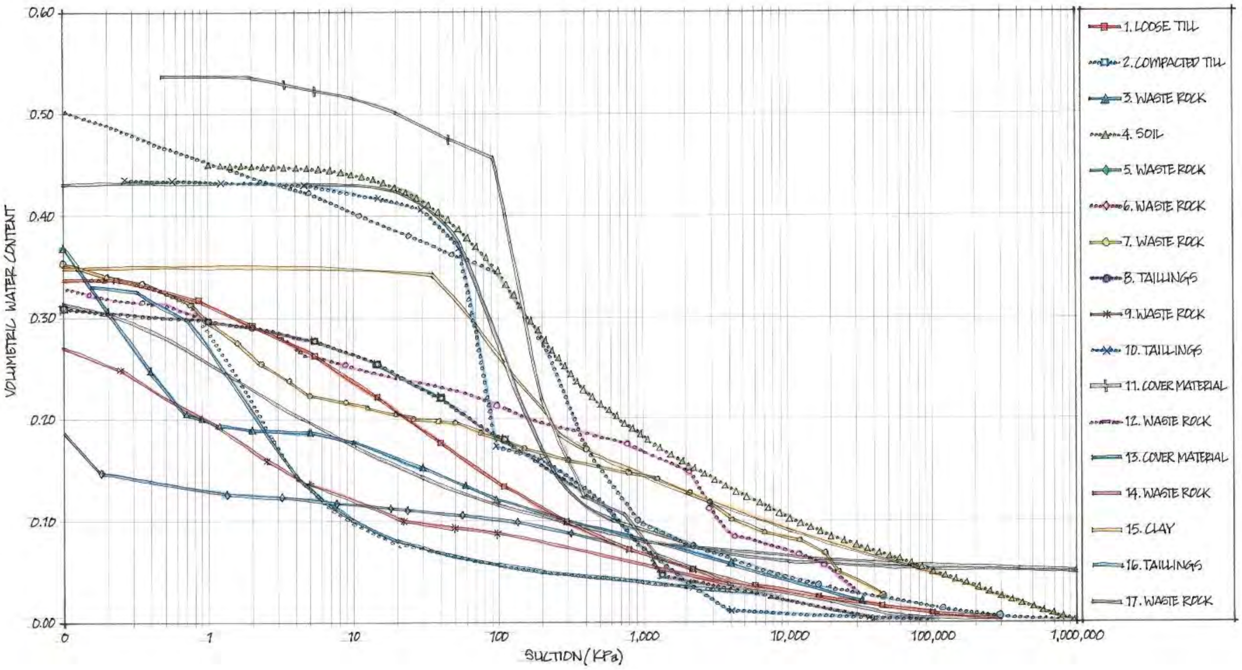


Figure 4-4. Water Retention Curves for typical mine materials (tailings, cover materials and barrier materials with increased fines retain more water for a given suction than waste rock). 1-3 (O'Kane et al., 1997), 4-5 (Reszat et al., 2009), 6-7 (Shurniak et al., 2009, 2012), 8-9 (Meiers et al., 2009), 10-11 (Duckett and O'Kane., 2006), 12-13 (O'Kane and Waters, 2003), 14-15 (DeVos et al.,1997; Ayres et al., 2005), 16-17 (Brett et al., 2011).

A material with a uniform particle size will tend to drain rapidly over a small range of suction values, because pore sizes are generally the same size. Well-graded materials with a wide distribution of pore sizes will have a WRC with a flatter slope.

4.3 Hydraulic Conductivity Function

The relationship that defines how water moves in the unsaturated zone is known as the hydraulic conductivity function (k-function). The hydraulic conductivity of a saturated soil is often assumed to be a constant for a given density or void ratio, whereas the hydraulic conductivity of an unsaturated soil will change with the volumetric water content. The k-function can also be described by a relationship between hydraulic conductivity and suction, as shown in Figure 4-5, because volumetric water content is related to suction through the WRC, which in turn is related to material texture.

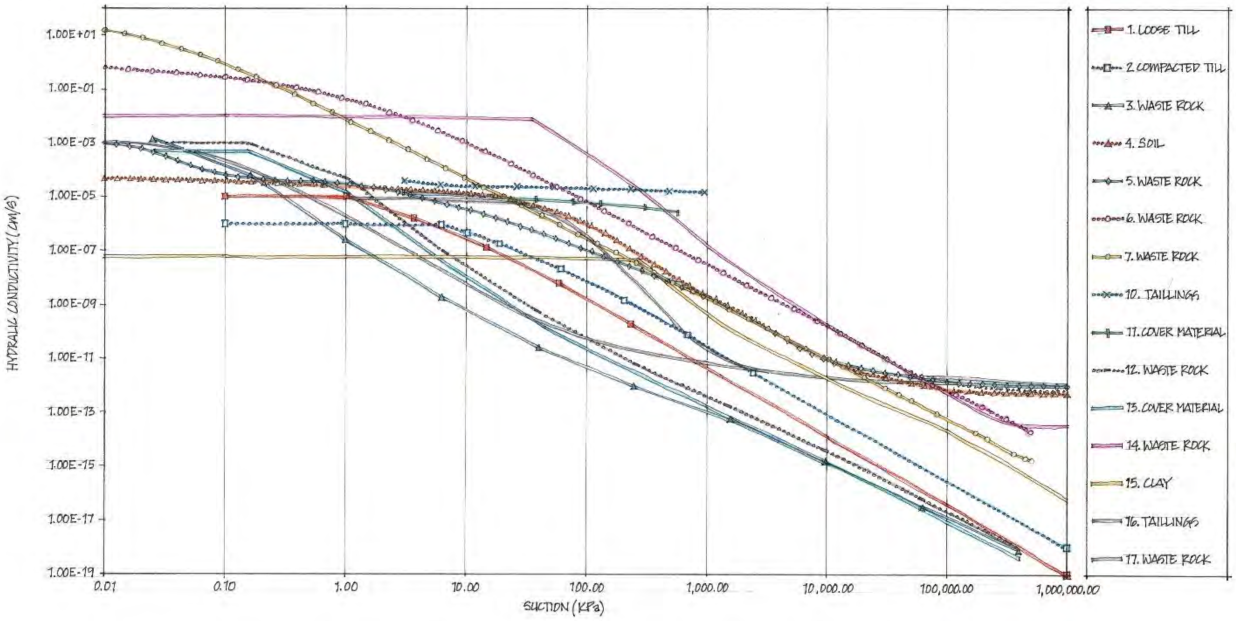


Figure 4-5. Hydraulic conductivity function plot. 1-3 (O'Kane *et al.*, 1997), 4-5 (Reszat *et al.*, 2009), 6-7 (Shurniak *et al.*, 2009, 2012), 8-9 (Meiers *et al.*, 2009), 10-11 (Duckett and O'Kane., 2006), 12-13 (O'Kane and Waters, 2003), 14-15 (DeVos *et al.*,1997; Ayres *et al.*, 2005), 16-17 (Brett *et al.*, 2011).

4.4 Available Water Storage Capacity

Available water storage capacity (AWSC) represents another key parameter, again related to the WRC and subsequently to material texture. AWSC is the volume of water stored within the rooting zone available for plant water use. In general, the rooting zone is taken to be one metre, but the actual value is site-specific. Although soils may exhibit similar AWSCs, an important consideration is field capacity in the context of the water balance and the manner in which textural discontinuities influence the water balance. This duration will be influenced by climate (frequency, timing, and rates of PPT delivery) and by factors that attenuate vertical drainage. Textural discontinuities have been shown to increase the amount of water held at field capacity and the duration over which these water contents are maintained compared with similar homogeneous soils (Huang et al., 2013). The combination of increased and prolonged water storage could have important implications for the design of reclamation cover systems over coarser-textured overburden and for the resulting hydrologic regime. The arrangement of materials and opportunity for layering warrants as much consideration as the physical characteristics of individual materials.

The required thickness and characteristics of the cover system layers will strongly influence the ability of the cover system to meet expectations. For example, if layers are not thick enough, tailings pore-water has been shown to be "pulled up" into the rooting zone, as a result of either advection (capillary rise), or diffusion.

B5. NEAR-SURFACE DENSITY CONDITIONS OF GROWTH MEDIUM LAYERS

Post-construction density of surface cover system layers is important where revegetation is planned. Compaction of growth medium layers that develops due to repeated equipment traffic must be addressed through ripping or other decompaction at the end of construction. If left intact, these compacted areas will hamper successful revegetation, and may lead to other issues, such as increased erosion downslope of the compacted area. Haugh (1995) suggests that successfully reclaimed land should have soil bulk dry densities of less than 1,600 kg/m^3 within 50 cm of the surface and 1,800 kg/m^3 within 100 cm. Compacted areas are treated through ripping or scarifying at the end of construction.

B6. MATERIAL EVOLUTION

The properties of a constructed cover soil will evolve over time as a result of weathering processes such as wet-dry or freeze-thaw cycles, geochemical weathering, or bioperturbation. The resulting changes in the pore structure of the soil will directly affect water storage and flow properties.

Freeze-thaw and wet-dry cycling affect cover system performance by creating soil macropores and influencing hydraulic characteristics (WRCs and k-functions). Growth medium layers will be subject to numerous wet-dry and freeze-thaw cycles, dependent on the site's climatic region. Certain materials may not hold up as well as others when subjected to the stress of climatic cycles and therefore the evolution of materials on hydraulic characteristics must be incorporated into design. Clays and materials with low initial hydraulic conductivity may experience increases of up to several orders of magnitude, which generally occur over the first few cycles. The effect of increasing hydraulic conductivity is most pronounced in compacted materials (Figure 6-1).

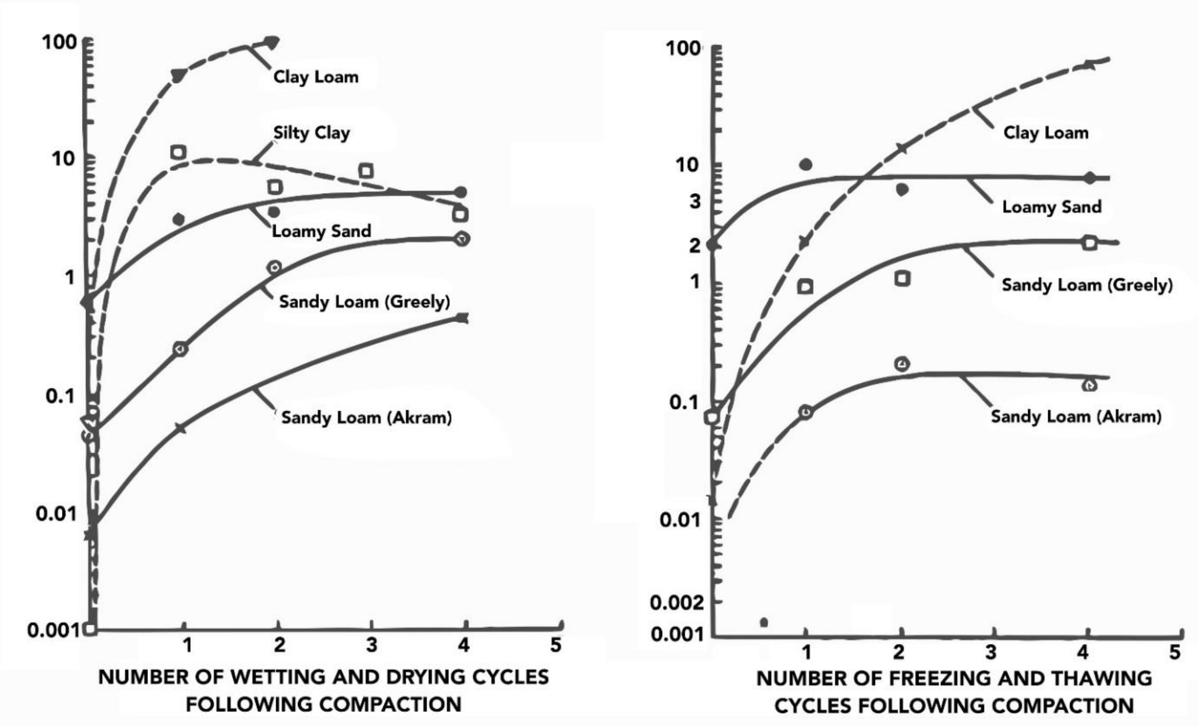


Figure 6-1. Evolution of hydraulic conductivity as a function of a) wetting and drying cycles, and b) freezing and thawing cycles for compacted layers (Gatto, 1997).

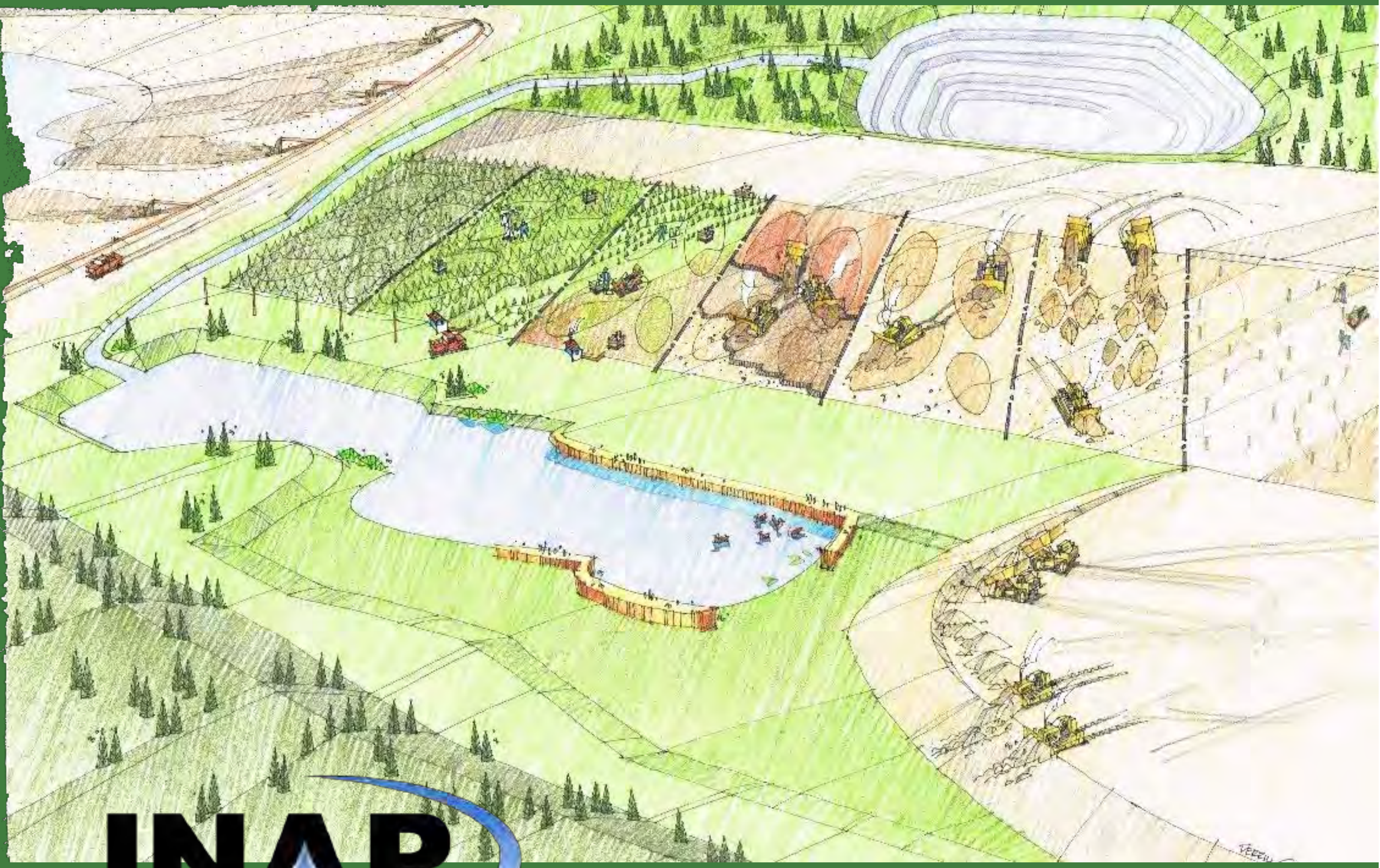
B7. MATERIAL SEGREGATION

Material segregation is another consideration that is often not accounted for in design but can occur due to construction practices. In addition, larger particles can be pushed progressively towards the surface as a result of freeze-thaw cycling in cold regions or through material handling methods. However, the same phenomenon may produce desirable surfaces in desert environments. This may be of particular concern when using well-graded till for a cover system, as the coarser fraction may gradually segregate and move to the surface (Bell, 1998).

Differential frost heave and settlement can occur across storage facilities in cold regions. Freezing depth can vary spatially due to variations in snowpack, depth to water table, slope aspect, and vegetation characteristics. In time, material segregation can affect freezing depth and lead to differential frost heave and settlement.

GLOBAL
COVER SYSTEM
DESIGN

APPENDIX C: HYDROGEOLOGY



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C1. Regional Setting

The regional hydrogeological setting includes physical hydraulic processes, such as recharge and discharge rates and locations, volumes and rates of water movement, and to water flow pathways. Faults and fractures may alter water flow rates. Identifying fractured media and preferential flow paths is also a significant component of characterizing hydrogeological settings as they provide pathways for the rapid mass transport of water or constituents of concern (COCs) from mine facilities to the receiving environment.

The geology of a site establishes the distribution and extent of the various hydrogeologic units that may act as either aquifers or aquitards. The geological setting also provides a framework for the regional geochemistry of the site. This might include buffering capacity, leaching potential, and weathering that might generate potential COCs. Locating a particular mine waste landform within the overall mine site context of the setting will influence long-term performance (e.g., whether it is located in a discharge or recharge area). Furthermore, determining the footprint of the landform in terms of contributing to groundwater may be a regulatory requirement.

The hydrogeological setting constrains the residence time and flux of sub-surface water. Groundwater modelling is a tool to identify critical components of the landscape, such as recharge and discharge zones, aquifers, and dominant flow paths. Modelling also allows designers to evaluate how landforms may alter the groundwater regime and whether a proposed landform will be a net benefit to cover system performance. Furthermore, it is important to understand how groundwater processes will evolve post-mining as a result of groundwater rebound and the system coming to a new equilibrium.

Although a hydrogeological setting can be altered, it requires substantial effort and expense in the form of grouting, re-contouring, cut-off walls, diversion structures, and large-scale earthworks. It is more advantageous to understand the hydrogeological setting of a site in hopes of incorporating natural geology into design, rather than incurring substantial costs to work against it. Furthermore, determining the geochemistry of a site provides another component of a full understanding of the hydrogeological setting. The interaction of mine wastewater with the background hydrogeological system may also provide passive treatment of mine effluent (e.g., buffering of effluent pH by carbonate-rich deposits, or clays with elevated cation exchange capacity for metal adsorption). The hydrogeological setting can act as a passive treatment method or potentially exacerbate issues if the hydrogeology or chemistry is not fully understood.

A common failure mode for cover systems can be traced to a lack of understanding of the regional hydrology. For example, highly engineered cover systems can fail to control effluent from a waste storage facility to the extent planned, simply because a substantive volume of water entering the facility was already flowing into the side of the pile laterally as groundwater (or run-on).

1.1 Location of Mine Waste Landforms within Hydrogeologic Setting

Mapping of regional recharge or discharge areas can help land managers mitigate contamination of aquifers or utilize containment provided by aquitards or barrier layers. Dewatering during mining tends to limit off-site migration of groundwater. However, the post-mining hydrogeology will evolve as groundwater levels are restored. The final, re-established hydrogeological setting will define water migration pathways, rates, and the water levels that will influence water management.

Water storage of a mined landscape is likely not in equilibrium with the watershed, while materials and landforms evolve under a dynamic climate, making it important to quantify antecedent water conditions. Hydrologic connectivity and flow of water in natural and reconstructed landscapes may be better understood and managed by a diligent consideration of this climate-geology interaction and the antecedent water conditions of the landscape and its components.

1.2 Integration of Cover Systems within Hydrogeological Setting

Although characterizing the hydrogeological setting is important, inevitable changes to the hydrogeological elements following implementation of a cover system must be anticipated. Integrating the design within the existing hydrogeological framework will require an assessment of water management needs for the landform, mine, and watershed. The four most common scenarios for managing water within the hydrological setting are to: keep all water on-site; divert "clean" water off-site before integrating it with regional groundwater; manage all affected waters on-site; and retain some water for on-site processes (Section 5.1.1).

The cover may alter local flow paths and partition more water from groundwater to surface water and change the storm response of receiving creeks or water bodies. Cover systems have the potential to change recharge and discharge locations and rates. The presence or absence of extensive thick, finer-grained clay layers and relative groundwater levels can delineate recharge and discharge type for basin-fill aquifers according to the methods of Anderson *et al.* (1994).

C2. Hydrogeological Control of Net Percolation

Geological setting and landform geometry affect geotechnical and geomorphic stability and influence dominant NP mechanisms. Consideration must be given to the resulting slope angles and slope aspects. The surface water balance changes substantially when slopes are introduced. Runoff, run-on, interflow, basal flow, seepage, ET, and NP rates are all directly, or indirectly, influenced by slope geometry. Slope also affects the surface energy balance in the form of micro-climatic conditions such as wind speed and direction, snow accumulation, and net radiation. In cold regions where the water balance and the energy balance are strongly coupled, the effects of topography are more pronounced.

2.1 Surface Geometry and Contouring

Surface geometry and contouring produces unique hydrology as a result of changes to insolation, surface water storage, runoff patterns, and micro-habitats for vegetation. Re-contouring slopes to include microtopography produces micro-sites for increased depression storage of surface runoff. This may be one strategy to employ in more arid climates, where vegetation establishment is required under climatic constraints. Moreover, depressions present unique micro-sites to enhance snow accumulation and prevent high-intensity runoff events (infiltration exceeds runoff). This may also provide an opportunity to store water and manage gas transport in climates or hydrogeological settings where it would otherwise not be possible, such as arid regions experiencing strong seasonality or monsoon events. Slope geometry presents unique challenges as well as opportunities in managing water on the landform.

The historical approach to material disposal and resulting slope configurations assumed it was better to limit slope length and erosion potential by establishing intermediate terraces (Walls, 2009). The relative importance of slope length and slope angle was not considered in many cases. But if surface water control structures failed on the benches, ponding would occur on flat areas, increasing infiltration and increasing the likelihood for overtopping to occur. It is now recognized that both climate and material characterization are the most influential components of slope angle and length.

2.2 Rainfall Intensity and Surface Conditions

The interaction of rainfall intensity, surface hydraulic conductivity, and the particular geometry of a cover system, as well as the material being used for the cover system, dictate to what extent surface water is redistributed prior to infiltration and discharge. Cover system design most often assumes that the water dynamics within the system are laterally uniform, with homogeneous material properties across the system. Local variability in soil properties can result in differences in runoff and infiltration. For example, increases in seepage at the base of the stockpile may be the result of lateral movement of water along layers of low hydraulic conductivity from areas of higher infiltration. Consideration must be given to where water accumulates in specific parts of the cover system. Depending on the intensity and duration of precipitation, the cover system may need to manage a large amount of water that can exceed a system's diversion capacity during parts of the year as indicated by the climate classification system (Aubertin *et al.*, 2006; Kämpf *et al.*, 2003; Zhan *et al.*, 2001).

2.3 Lateral Diversion

Diversion length along a sloping landform are considered when textural contrasts are part of the cover system (e.g., capillary breaks and compacted layers). Diversion length is defined as the length of sloping interface until breakthrough of water occurs. In the case of a capillary break cover system, this will occur at the point along the interface where matric suction in the finer-textured overlying layer equals the air entry value (AEV) of the coarser-textured underlying layer. The ability to divert water laterally is strongly related to the hydraulic conductivity of the overlying finer-textured layer of cover material, the slope angle of the interface of the textural discontinuity and the underlain coarser-texture layer. The contrast in texture between the coarser- and finer-textured materials can also influence the diversion length.

Numerous analytical solutions are available to estimate diversion length and corresponding flow capacities of idealized sloped cover systems, and have mostly been developed from the same assumptions (Lu and Likos, 2004; Rossi and Nimmo, 1994; Warrick *et al.*, 1997).

C3. Hydrogeological Control of Oxygen

Storage facility geometry can be a controlling factor for airflow. To highlight the importance of material geometry as it pertains to controlling oxygen ingress, three storage facility geometries typical of mine waste storage facilities are presented:

1. Finer-textured, lower permeability, tailings storage facility;
2. Backfilled pit with a re-established water table; and
3. A waste rock pile with an upper plateau and steeply sloping sides.

3.1 Tailings Storage Facility

The dominant mechanism in controlling oxygen ingress in a tailings storage facility (TSF) is most often diffusion transport (Figure 3-1). Advection and convection are often of minimal concern due to the use of shallow-sloping, low-permeability tailings dam walls and embankments to contain saturated tailings. Elevated water contents decrease air permeability at the surface boundary of the tailings, limiting the ingress of oxygen to diffusion alone; saturated cover systems may be used to further decrease oxygen diffusion coefficients. Furthermore, finer-textured tailings also retard the flow of oxygen within the facility due to decreased air permeability, higher saturation conditions, and therefore lower diffusion rates.

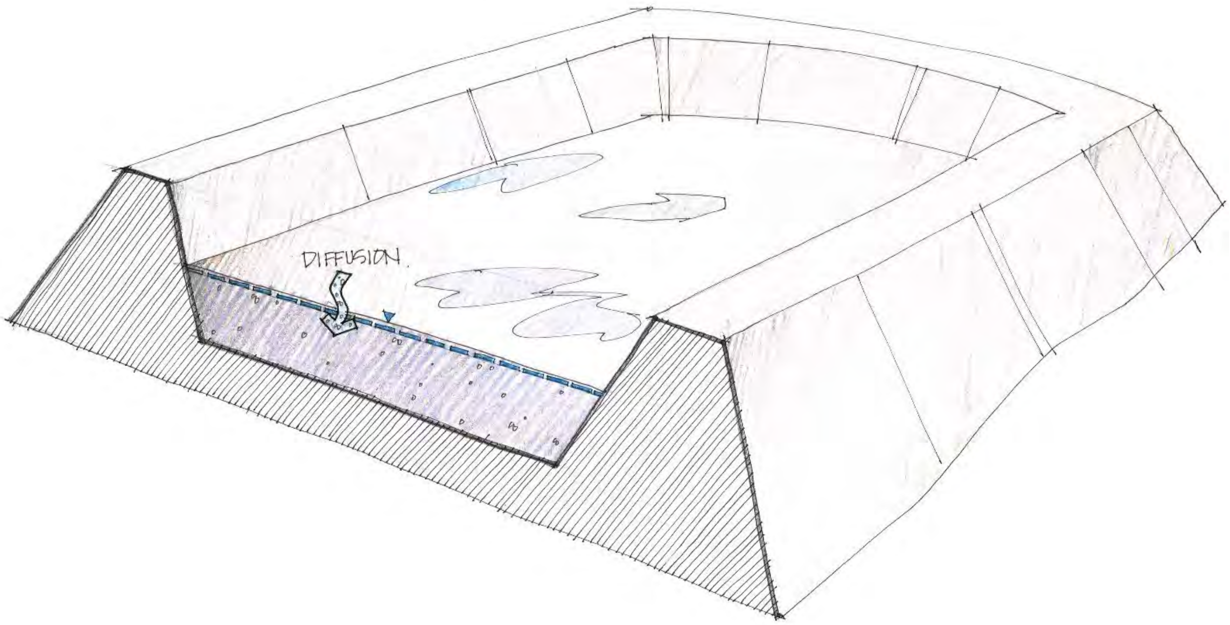


Figure 3-1. Geometrical control of oxygen ingress to restrict diffusion into a TSF landform.

3.2 Back-Filled Open Pits

Back-filled pits are similar to a TSF from a gas transport perspective. The geometry of back-filled pits with confined sloping sides "sheltered" from the atmosphere is not conducive to large advective or convective flows, providing there are no artificial faults (adits) or natural faults that act as conduits for oxygen. Oxygen transport into back-filled pits must occur through diffusion at the upper boundary layer (Figure 3-2). Provided a water table rebounds and reaches a stable equilibrium, oxygen diffusion can be managed similar to a saturated cover system. Alternatively, if back-filled materials are not inundated, further cover system alternatives can be employed to manage oxygen ingress to exposed back-filled materials (e.g., a cover system with a CCL that maintains tension saturated conditions as per Ayers *et al.*, 2012).

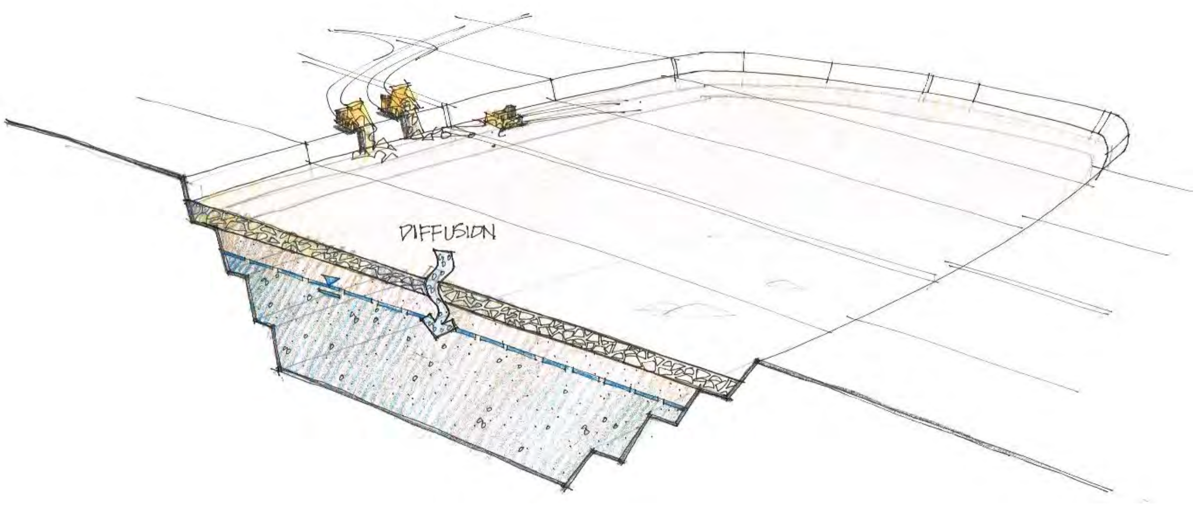


Figure 3-2. Geometrical control of oxygen ingress to restrict diffusion into a back-filled pit landform.

3.3 Waste Rock Dumps

Waste rock dumps (WRDs) pose the greatest susceptibility to mass oxygen ingress, largely due to their constructed geometry. Results have shown that hindering oxygen ingress into reactive mine material is an effective control method, particularly on relatively flat areas. However, the geometry encountered on some landforms, such as large tailings dykes and WRDs, makes it challenging to maintain an effective oxygen barrier along the entire sloping area because of local desaturation of the water retaining layer (Aubertin *et al.*, 1997; Bussière and Aubertin, 2003; 2000; Bussière *et al.*, 1998), as well as small cracks and fissures in the cover layers (Figure 3-3).

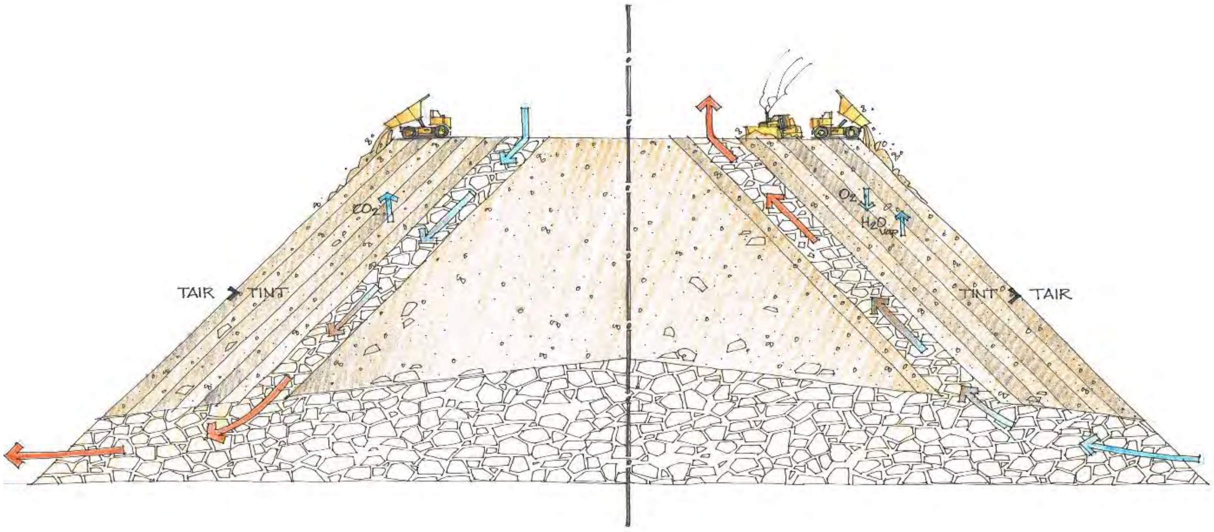


Figure 3-3. Geometrical control of oxygen ingress processes into a waste rock landform (Tair = external temperature. Tint = internal temperature).

Pile geometry, namely slopes created by end-dumping and/or pushing, can induce convection regardless of the particle size distribution or permeability of the materials contained within the pile (Lefebvre *et al.*, 2001c). Geometry-induced differences in oxygen ingress have also been demonstrated in tailings storage facilities. Three years of monitoring at the Les Terrains Auriferes tailings site recorded an average value for oxygen consumption on top of the covered system of 13 moles $O_2/m^{2/}yr$, while oxygen consumption of the outer slopes reached 34 moles $O_2/m^{2/}yr$. To support large oxygen consumptions on the outer slopes with an otherwise limited internal oxygen level, convection played a larger role in supplying oxygen to the reaction on the side slopes compared with the top cover (Aubertin et al, 1999).

The more permeable the waste material and the greater the height to width ratio of the storage facility, the greater the potential for advective air movement. Therefore, the height and slope of the WRD should also be considered when trying to control convection (Kuo and Ritchie, 1999). Many of the issues governing convective and advective transport can be minimized through WRD construction practices.

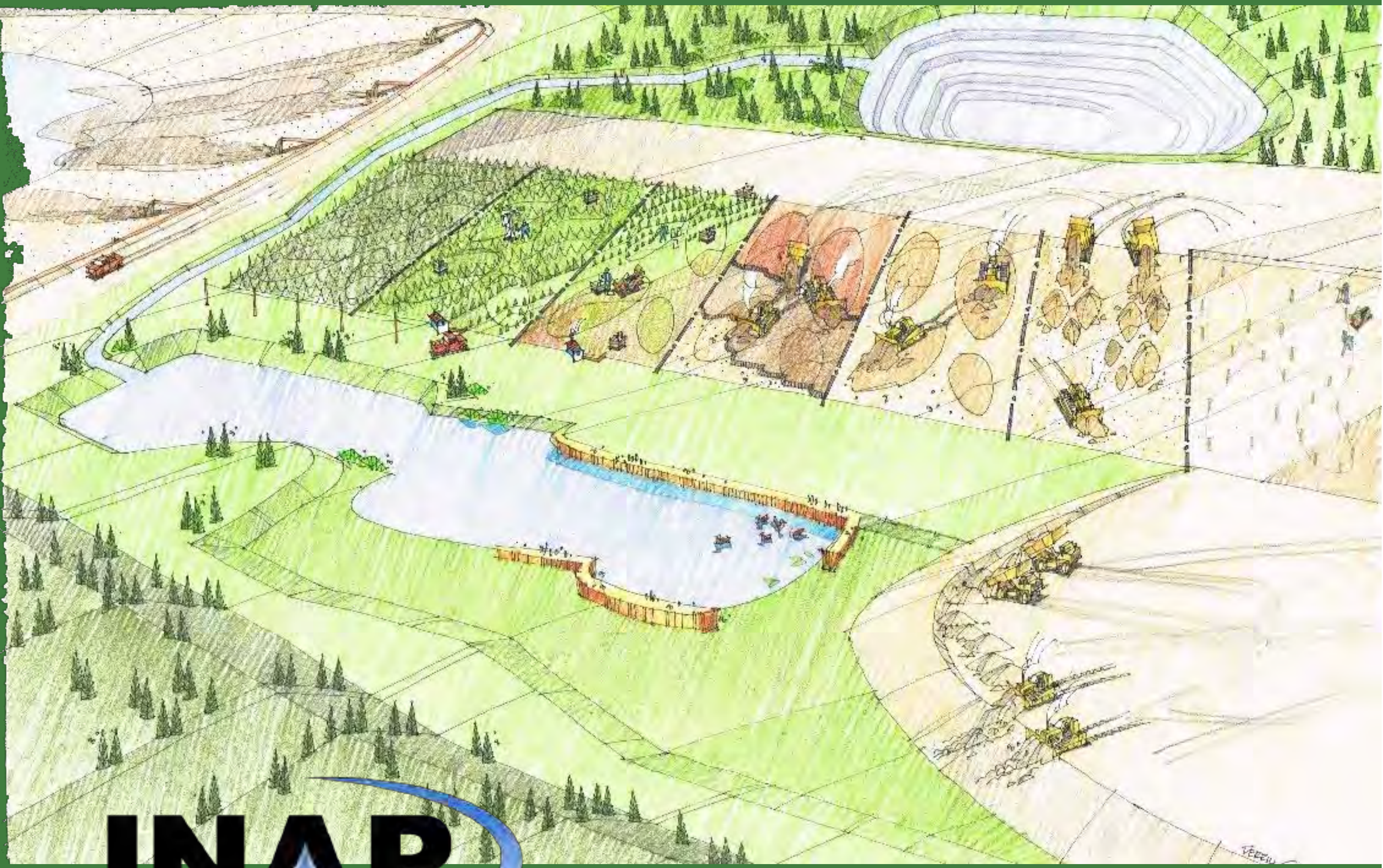
End-dumping over the face of a waste rock dump is common, but it results in sorting by gravity, which produces coarse basal boulder zones and sloping inter-bedded layers of coarser- and finer-textured material (Herasymuik, 1996; Wilson *et al.*, 2000). Finer-textured layers provide lateral diversion for water flow into the pile, while the boulder zone at the toe, or at the base of a lift of waste rock, allows for influx of oxygen-rich air. Sloping coarser-textured layers vent warm gases to the surface in a manner like that of a chimney. Depending on the construction geometry, high vertical permeability can result, enhancing conditions where convection is a dominant gas-transport mechanism.

Shallower lift heights and block dumping by haul trucks will substantially decrease the potential for advective gas transport within a WRD. In some cases, this will add substantial costs and must be evaluated against the benefits gained. Constructing WRDs with a greater number of lifts also allows for opportunities for highly trafficked surfaces on which haul trucks create horizontal compacted layers with a lower air/water permeability. Compacted layers can act as textural discontinuities to the surrounding material and, potentially, vertical barriers to water and gas flow. Through innovative WRD design, low-permeability, potentially acid-neutralizing layers can encapsulate reactive materials before acid-generating conditions develop (Day *et al.*, 2000). Co-disposal of tailings and waste rock during construction of the storage facility can also introduce fines to an otherwise lack of grain-supported matrix, allowing oxygen transport to be managed to a greater extent.

Demonstrating the merits of this type of approach to WRD landform construction are challenging in regards to immediate mining costs and long-term closure. Hence, it can be challenging to implement different WRD construction approaches. However, the key to cost-effective management of ML/ARD during operations and at closure is finding a compromise between mine planning and closure planning such that the two are brought together within a single plan throughout the LOM. While a cover system is the final stage in the construction of an engineered landform, there are benefits to evaluating alternate WRD construction approaches so that performance expectations on the final cover system are not as stringent and the cover system, and/or some collection and treatment system, are not viewed as the sole measure for managing ML/ARD. A well-constructed reactive material storage facility in combination with an appropriate cover system can further optimize the economics of a project, due to both components leading to reduced long-term costs associated with managing reactive waste material.

GLOBAL
COVER SYSTEM
DESIGN

APPENDIX D: TOPOGRAPHY



International Network for Acid Prevention

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D1 Surface Energy Balance

The surface energy balance describes the net change in energy at the surface over a given time period. Energy comes largely in the form of short- and long-wave solar radiation, heat from the phase change of water, and conduction of heat from the surrounding soil. Energy is lost from the surface as outgoing infrared radiation, heat removed from the phase change of water, and conduction of heat to the surrounding soil. The basic energy balance equation (Oke, 1996) is:

$$\mathrm{Q}^{*} = Q_H + \mathrm{Q}_E + \mathrm{Q}_G$$

where Q^{*} represent net radiation, Q_H = sensible heat, Q_E = latent heat, and Q_G is ground heat flux (all units in W/m^2). The radiative energy delivered to the earth depends on seasonality, latitude, and aspect. Energy is the highest and most consistent throughout the year at the Equator. As one moves away from the Equator, both peak and minimum energy decrease.

D2 Slope and Aspect

Solar aspect is defined as the compass direction a slope faces, and influences the total energy received by the surface. For example, in the northern hemisphere, south-facing slopes are exposed to higher solar energy input than north-facing slopes. The effect of slope and aspect is magnified in high latitude climates – compared with low latitude climates – where the lower sun angle results in greater variation in both seasonal and spatial variation in net radiation.

In middle to high latitudes, slope direction is critical to the thermal balance. At equatorial latitudes, the sun angle is high overhead, distributing energy relatively equally on all slope aspects. In arctic latitudes, the sun is low on (or below) the horizon, providing little energy in winter at solar noon. When the angle at which solar radiation strikes the surface reaches its maximum during summer, radiation is more evenly distributed on all solar aspects with each rotation of the Earth.

Swift (1976) developed an algorithm for adjusting incoming solar radiation for varying slopes and aspects. For example, a 3:1 north-facing landform slope near Elko, Nevada, would have 29% lower net radiation than a level slope and a south-facing 3:1 slope would have 24% higher net radiation (based on Zhan *et al*., 2006).

Slope and aspect affect many processes on a micro-scale, such as snow accumulation, frost penetration, snowmelt, day length, growing season length, and ET. They may become one design tool used to manipulate the energy balance of a landform to achieve more desirable performance of NP or oxygen ingress. That tool is linked to the water balance. Slope and aspect effects largely involve surface water movement on landforms. In systems with little connection to the water table, topography will determine watershed catchments and the movement of water according to hydraulic gradients. The re-distribution of water on cover systems from sloped to plateau or bench regions should lead to unique segmented cover system strategies.

D3 Elevation

Elevation influences the local energy balance through the effects associated with air parcel buoyancy. Energy at a valley bottom may flow to mid or high elevations, and vice versa, due to a pressure difference. As an air parcel rises and pressure falls, the parcel expands and cools. The process contributing to changes in temperature with elevation, the environmental lapse rate, is a unique micro-climatological element considered in cover system design, particularly at high elevations.

Spatial differences in the water and energy balances are important considerations for storage facilities at a variety of scales. Spatial as well as temporal dimensions (timing, intensity, and duration of energy), both play a role. Processes such as snowmelt, transpiration and evaporation represent mechanisms combining attributes of the energy and water balances.