Updates to the Yukon Geological Survey's mineral potential mapping methodology

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Abstract

This paper serves as an update to an earlier paper published by the Yukon Geological Survey: *New mineral potential mapping methodology for Yukon: case studies from the Beaver River and Dawson regional land use planning areas* (Bullen, 2020). Since the release of the earlier paper, a number of the methods have been modified, and new techniques introduced. These are incorporated into this update paper — the reader is referred to the earlier paper for details of the method itself.

Mineral potential maps have thus far been completed for the Beaver River watershed, and the Dawson, Teslin, Na-Cho Nyäk Dun, and Ross River regions.

There have been significant updates made to the mineral potential mapping method:

1. Modifications to buffer distance and factors (these are an important fuzzy logic (*i.e.*, non-Boolean) component of the mineral potential mapping process) to enhance mapping outcomes.
2. The introduction of an in-house generated, machine learning algorithm (unsupervised, clustering-type) to classify mineral potential in order to remove the potential for human bias. The method replaces the statistical, areas-under-the-curve approach used previously.
3. A new method for delineating anomalous stream sediment data based on the lithological makeup of each watershed basin. The method computes and compares expected assay values to actual assay values, with values exceeding a certain threshold taken as anomalous. The previous method did not take lithology into account, relying on simple percentile methods only, and was considered insufficiently robust.
4. A new method for categorizing mineral potential confidence. Mineral potential maps produced by the Geological Survey contain measures of bedrock mapping confidence to facilitate land use planning. The updated method is significantly more robust than that used previously.
5. Revisions to the map legend to account for the new, machine learning-based mineral potential categorization methodology.
6. Revisions to the map colour scheme to make them colour blind-safe.

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Introduction

In December 2019, the Yukon Geological Survey (YGS) published a paper entitled: *New mineral potential mapping methodology for Yukon: case studies from the Beaver River and Dawson regional land use planning areas* (Bullen, 2020). Since then, some of the methods have been modified and new techniques introduced, with the aim of enhancing the quality and robustness of mineral potential maps produced by the YGS. This paper serves as an update to the earlier paper.

The reader is referred to the earlier paper for an explanation of the mineral potential mapping methodology used by the YGS, along with its development and implementation in land use planning activities in Yukon.[1]

Updates and New Techniques

Mineral potential maps using YGS's original methodology were completed for the Beaver River watershed and Dawson region land use planning exercises. Mineral potential maps have also been completed for the Teslin Tlingit Council Traditional Area, Traditional Territory of the Na-Cho Nyäk Dun First Nation and the Ross River Dena Council Traditional Area (Fig. 1); these three will be updated in line with the new techniques noted below prior to the initiation of land use planning exercises in these areas.

As detailed in Bullen (2020), the mineral potential mapping procedure uses a generalized minerals systems approach and utilizes block modeling techniques where each block (unit cell) is assigned a prospectivity score and, separately, a confidence score. Scores are calculated based on the presence or absence of categorical features within unit cells and represent the posterior favourability of each unit cell relative to other unit cells. The posterior favourability refers to mineral potential and confidence scores after all evidence has been taken into account. Evidential layers are weighted according to buffer distance and/or through the application of knowledge-based factors. Lithology classes are an exception – these features are factored using a multiclass weights of evidence (WofE) approach with known mineral occurrences used as training points.[2]

The process thus differs to pure data-driven mineral prospectivity mapping, being a hybrid between a classic data-driven probabilistic WofE approach (which uses a binary value assessment, *i.e.*, 0/1) and an expert-driven fuzzy logic[3] approach, the latter providing the advantage of allowing the user to assign a membership value anywhere between 0 and 1 (*i.e.*, 0, 0.01, 0.02,...0.98, 0.99, 1) for any predictive input parameter.

Factors and buffers are an important fuzzy logic (*i.e.*, non-Boolean) component of the mineral potential mapping process. The choice of buffer distance in the case of point, line (and less commonly polygonal) data, and the selection of weighting factors in the case of polygonal data, is critical to a successful outcome. Expert input is key in this respect.

Table 1 shows the modified buffer distances and factors implemented subsequent to the Beaver River watershed and Dawson region mineral potential mapping exercises.

Mineral Potential Categorization

Prior to 2020, the mineral potential of areas in Yukon was categorized as highly prospective, significantly prospective and moderately prospective based on defined standard deviations (Bullen, 2020). The method involved transforming the data (if significantly skewed), converting the transformed data to a standardized normal distribution (with a mean of 0 and a standard

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[1] *In Yukon (and elsewhere), land use planning refers to the process whereby land use (e.g., hunting, fishing, mining, agriculture, forestry) is codified. Protected areas such as parks are another outcome of land use planning. The process is overseen by government (territorial and First Nation) appointees who make recommendations based on feedback from land use planners, who rely, in turn, on input from government, non-governmental agencies, and the general public.*

[2] *In weights of evidence prospectivity mapping, a categorical feature/evidential layer is a spatial theme (i.e., a data layer such as bedrock geology, faults, etc.) used as evidence for the occurrence of training points. Each categorical feature occupies a defined area. Training points are the set of spatial point objects whose locations are to be predicted. In mineral exploration, these are the sites of known mineral deposits or occurrences, with the points being either present or absent.*

[3] *Fuzzy logic is an approach to computing based on "degrees of truth" rather than the usual "true or false" (1 or 0) Boolean logic on which the modern computer is based (https://searchenterpriseai.techtarget.com/definition/fuzzy-logic). The concept, first put forward by Lotfi Zadeh in the 1960s, has wide application in today's world – e.g., gear selection in vehicles, cycle selection in dishwashers, copy machines. An example of Boolean logic versus fuzzy logic (taken from techtarget, 2021) is the response to the question "is it hot"? Boolean logic calls for a "no/yes" (0, 1) response whereas a fuzzy logic response might be "somewhat", "moderately", "fairly so" (0.25, 0.50, 0.75), etc.*

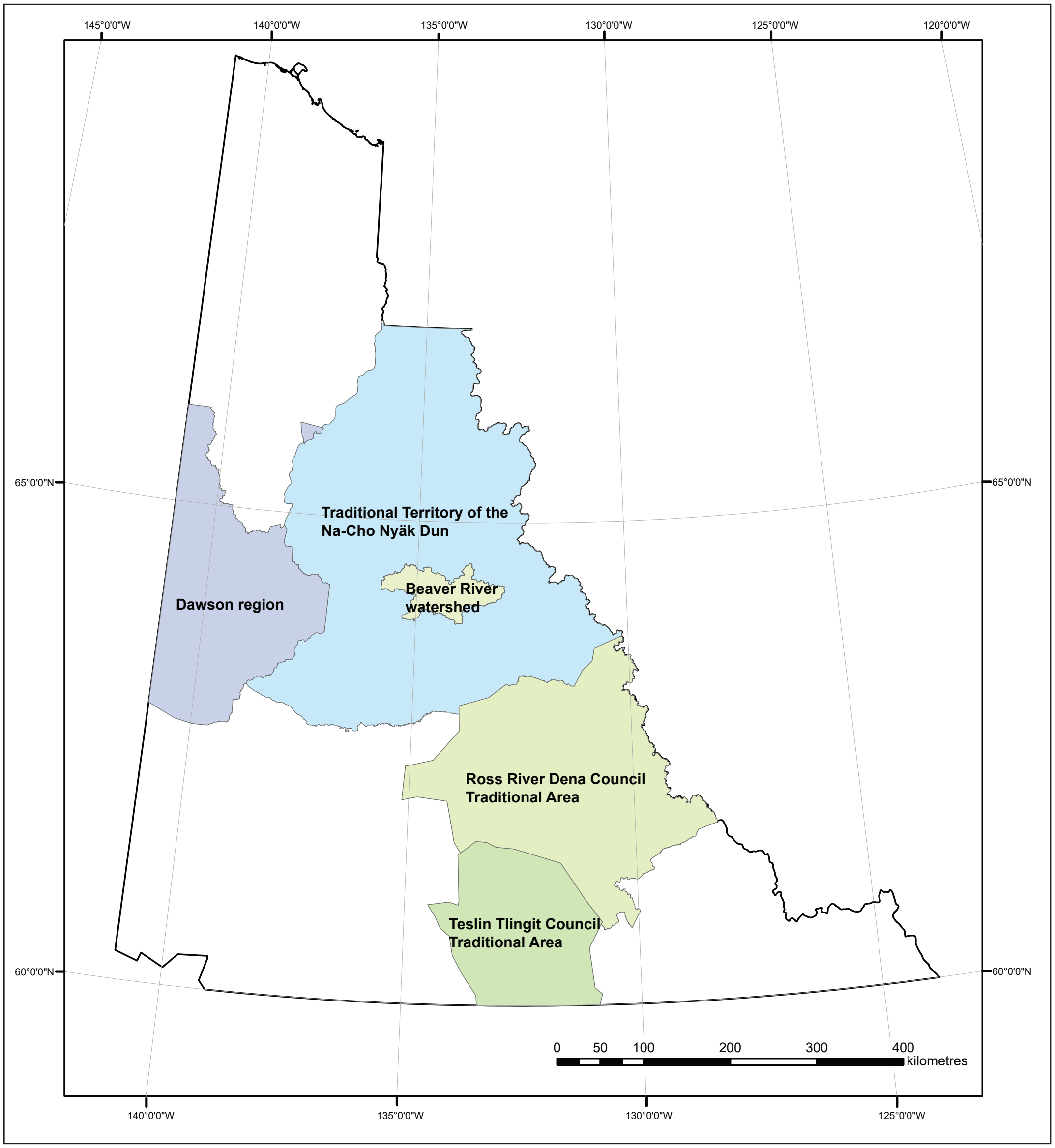

***Figure 1.** Mineral potential mapping coverage in Yukon using the Yukon Geological Survey's new mineral potential mapping methodology. The Dawson region and Beaver River watershed mineral potential maps are in the public domain – the remainder are internal working documents at this time.*

deviation of 1), and then assigning values of 1, 2 or 3 to the normalized scores as follows:

1. Scores falling below a StDev of –1 (encompassing approximately 16% of the data) were assigned a value of 1 and were designated "Moderately prospective";
2. Scores falling between a StDev of –1 and +0.5 (approximately 53% of the data) were assigned a value of 2 and were designated "Significantly prospective"; and
3. Scores falling above a StDev of +0.5 (approximately 31% of the data) were assigned a value of 3 and were designated "Highly prospective" (Fig. 2).

The method worked well, and the outcomes were readily accepted by land use planning bodies and other stakeholders. However, the process was command-based, and the mineral potential category boundaries were (somewhat) arbitrarily defined with the potential for human bias. The outcomes were therefore, at least in principle, difficult to defend. Consequently, the author elected to move towards a purely data-driven classification scheme based on data distributions and patterns. To this end, a machine learning algorithm (unsupervised, clustering-type) suitable for mineral potential classification was developed, with the key goal being the removal of subjective input.

Table 1. *Updated factors and buffers used in mineral potential mapping post the Beaver River watershed and Dawson region mapping exercises.*

Bedrock geology weighting factors (YGS, 2021a).

Technique	Polygonal data	Method	Factors applied
Multiclass weights of evidence (see Bullen (2020) for details)	Rock subclass	Contrast values generated using weights of evidence, mineral occurrences used as training data, contrast values scaled from 0 to 1, square root transformation applied to reduce skewness, values converted to a standardized normal distribution and factored	StDev > 2.0 = 1.5
			1.5 < StDev ≤ 2.0 = 1.4
			1.0 < StDev ≤ 1.5 = 1.3
			0.5 < StDev ≤ 1.0 = 1.2
			0.0 < StDev ≤ 0.5 = 1.1
			-0.5 < StDev ≤ 0.0 = 0.9
			-1.0 < StDev ≤ -0.5 = 0.8
			-1.5 < StDev ≤ -1.0 = 0.7
			-2.0 < StDev ≤ -1.5 = 0.6
			-2.0 > StDev = 0.5

Plutonic rocks (YGS, 2021a).

Lithology	Buffer	Factor	Rationale
Felsic to intermediate igneous pluton rocks of Jurassic age and younger	2000 m	None	Estimate of potential influence of intrusion away from contact, must be supported by aeromagnetic data, aeromagnetic “haloes” must be unrelated to bedrock geology

Mineral occurrence data (YGS, 2021b).

Deposit type	Buffer	Factor	Rationale
Past producer/producer	2000 m	None	Relative importance of categorical feature
Deposit	1000 m		
Anomaly/drilled prospect/prospect	500 m		
Showing	250 m		
Unknown	100 m		

Fault data (YGS, 2021a).

Fault category	Ring buffers	Factors	Rationale
Major faults	2000 m, 1000 m, 500 m	1, 1.5 and 2, respectively	Relationship between structure and sites of potential mineralization, influence of categorical feature decreases away from feature
Other faults	1000 m, 500 m	1 and 1.5, respectively	

Fold data (YG, 2021a).

Fold category	Buffer	Factors	Rationale
All folds	500 m, 250 m	1 and 1.25, respectively	Relationship between structure and sites of potential mineralization, influence of categorical feature decreases away from feature

***Table 1** continued.*

Stream sediment geochemistry (YGS, 2021c).

Commodities	Method	Rationale
Primary commodities covering deposit types of interest	Method involves calculating expected stream sediment values and comparing these to the actual values obtained	Lithological makeup of drainage basins the key factor in understanding and identifying anomalies – see below for detailed explanation

Placer claims (YG, 2021b).

Claim category	Buffer	Factor	Rationale
Historic Placer claims	None	0.5	Relatively low factor given that historic and current placer claims potentially overlap, and in which case are additive
Current Placer claims and leases		1.5	Potential economic importance high relative to spatial extent of claims, higher factors allocated
Current Placer claims – Class 3		2	
Current Placer claims – Class 4		2.5	

Quartz claims (YG, 2021c).

Claim category	Buffer	Factor	Rationale
Historic Quartz claims	None	0.5	Relatively low factor given that historic and current quartz claims potentially overlap, and in which case are additive
Current Quartz claims and leases		1	Includes Class 1
Current Quartz claims – Class 2		1.25	Considered to be prospective
Current Quartz claims – Class 3		1.5	Considered to be significantly prospective
Current Quartz claims – Class 4		1.75	Considered to be highly prospective
Current Quartz claims – Class 5		2	Potentially economic

Assessment reports (YGS, 2021d).

Assessment reports	Buffer	Factor	Rationale
Assessment report footprints	None	Varies from 1 to 3 depending on degree and extent of overlap (calculated using ArcMap routines)	Assessment work carried out over the same area more than once (in some cases numerous times) – depends on the perceived prospectivity of the area

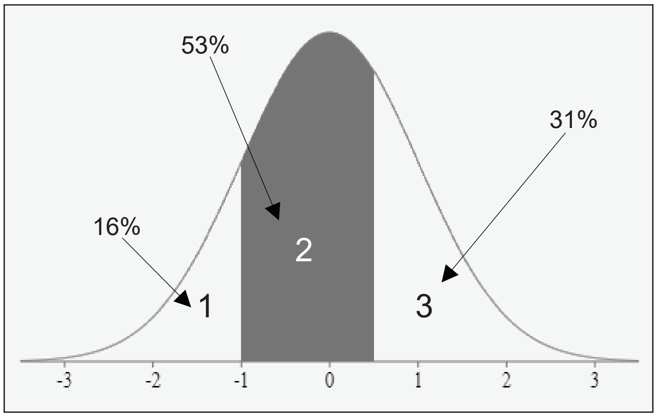

Figure 2. *Normally distributed data showing the areas-under-the-curve method used previously by the Yukon Geological Survey to classify mineral potential. In practice, the normalized scores did not align to a perfect normal distribution, so the mineral potential area percentages varied to a small degree.*

The machine learning algorithm developed by the Yukon Geological Survey uses an iterative, value-optimization approach. To achieve this, the concept of value was introduced into the machine learning process (Bullen, 2021). The resultant machine learning decision model is both intuitive and defendable, and has other applications beyond mineral potential domaining — for example, determining the opportunity cost of land withdrawal alternatives stemming from a land use planning exercise, and value-add multiple mapping (these are beyond the scope of this paper and are not discussed further).

An in-depth description of the machine learning algorithm is given in Bullen (2021), and the reader is referred to this article for further details.

The machine learning decision model delineates four clustered, value-optimized land parcels of decreasing mineral potential. The land parcels are denoted Optimally prospective – Level 1; Optimally prospective – Level 2; Significantly prospective; and Moderately prospective. To delineate the area categorized as Optimally prospective – Level 2, cells falling within the area designated Optimally prospective – Level 1 are removed from the model and algorithm is run without these cells. To delineate the area categorized as Significantly prospective, cells falling within the Optimally prospective – Level 1 and 2 domains are removed and the algorithm rerun, and so on. In all cases the procedure is the same. Clearly, an infinitely large number of mineral potential categories could be derived but this is impractical, as the four categories noted above more than adequately capture variations in mineral potential (Fig. 3). Figure 4 shows the mineral potential map for the Dawson region (excluding, for clarity, measures of confidence – see Bullen, 2020). Cell boundaries are clearly evident in Figure 4 (*i.e.*, no smoothing has been applied) – each cell contains a unique mineral potential score which has been colour-coded according to the value-optimization machine learning prospectivity categories noted in Figure 3.

Processing Stream Sediment Data

Stream sediment anomalies in the Beaver River watershed and Dawson region were previously identified using simple standard deviation and percentile methods (Bullen, 2020). These methods are regarded as insufficiently robust as they do not take lithology, which plays a key role in anomalous value determination, into account. Work by Mackie et al. (2015) on stream sediment data in Yukon showed that lithological variation exhibited a significant control on the distribution of a number of important commodity and pathfinder elements. Consequently, stream sediment data used for mineral potential mapping are now assessed after taking the lithological makeup of each watershed basin into account.

The method involves calculating the expected stream sediment assay values at each drainage sample collection point (located at the outflow point of each defined watershed basin). Built into the method is the understanding that watershed basins of differing orders are superimposed on each other. For example, basins sampling first order streams are superimposed on basins sampling second order streams and so on, with each basin having a unique stream sediment geochemistry (and a unique sample attached to it). From a mineral potential mapping point of view, anomalous basins are additive in the sense that the mineral potential of a first order basin is added to the mineral potential of a second order basin (and so on), if both are anomalous (otherwise they are not additive but are treated, rather, as distinct entities). This is the desired outcome in terms of the mineral potential mapping methodology.

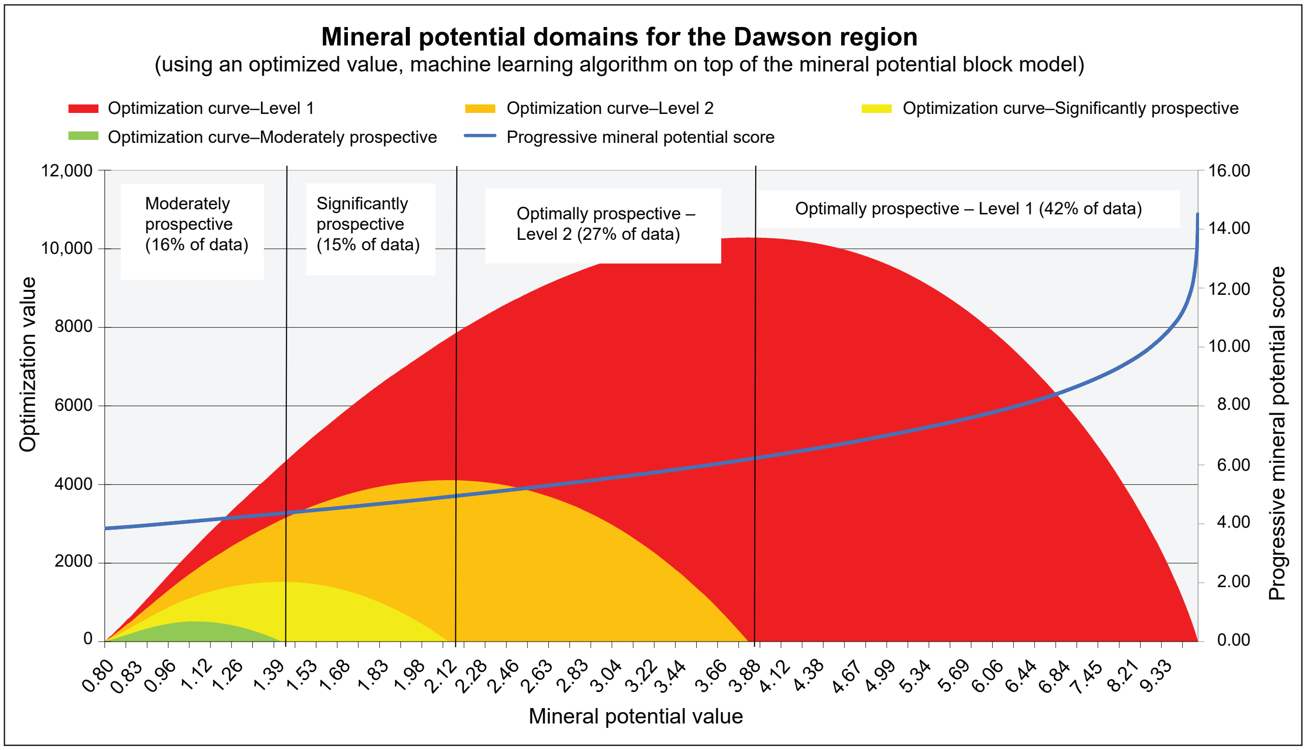

Figure 3. *The machine learning decision model showing mineral potential domains for the Dawson region. The percentage area covered by each domain is shown. The value-optimization measures the total value-add at any point along each of the four curves, which initially increases but then decreases as cells continue to be removed – i.e., after the remaining area drops below a certain threshold. Removal of any cell within a mineral potential category results in a drop in the optimized value. See Bullen (2021) for further details.*

Anomalous stream sediment values are calculated by comparing the expected, lithology-dependent, stream sediment values with the actual values obtained. Each watershed basin is examined separately. Once the expected values are known, anomalous values are taken as those exceeding the 97th percentile.

The process is carried out in ArcMap and is noted below in simplified form:

1. Separate tables for each commodity element of interest are prepared – each table contains the sample ID and assay value fields;
2. The watershed basin and bedrock geology layers are intersected, with the output layer constrained to lithology (at the 250K scale);
3. The spatial extent of each watershed basin, and of each lithological unit within each watershed basin, is calculated;
4. The expected commodity element "grade" of each lithological unit in each drainage basin is calculated using the drainage sample values for each basin split proportionally between the units. The assumption is that each lithological unit in each watershed basin contributes to the stream sediment load in proportion to the area they occupy;[4]
5. The expected average "grade" for each lithological unit within the area of interest as a whole is calculated by averaging the "grade" of each lithological unit within each drainage basin;

[4] *While this assumption may at first appear to have some limitations – given that rock units weather at different rates, and are chemically distinct from each other – the process of anomaly determination is dependent on both the lithological makeup of individual basins and the lithological makeup of the area as a whole. Expected values are calculated on the back of numerous different lithology combinations of widely differing proportions, so that differing rates of weathering are effectively captured (through a process of averaging, or smoothing), and subsequently applied to individual watersheds for determination of anomalous values.*

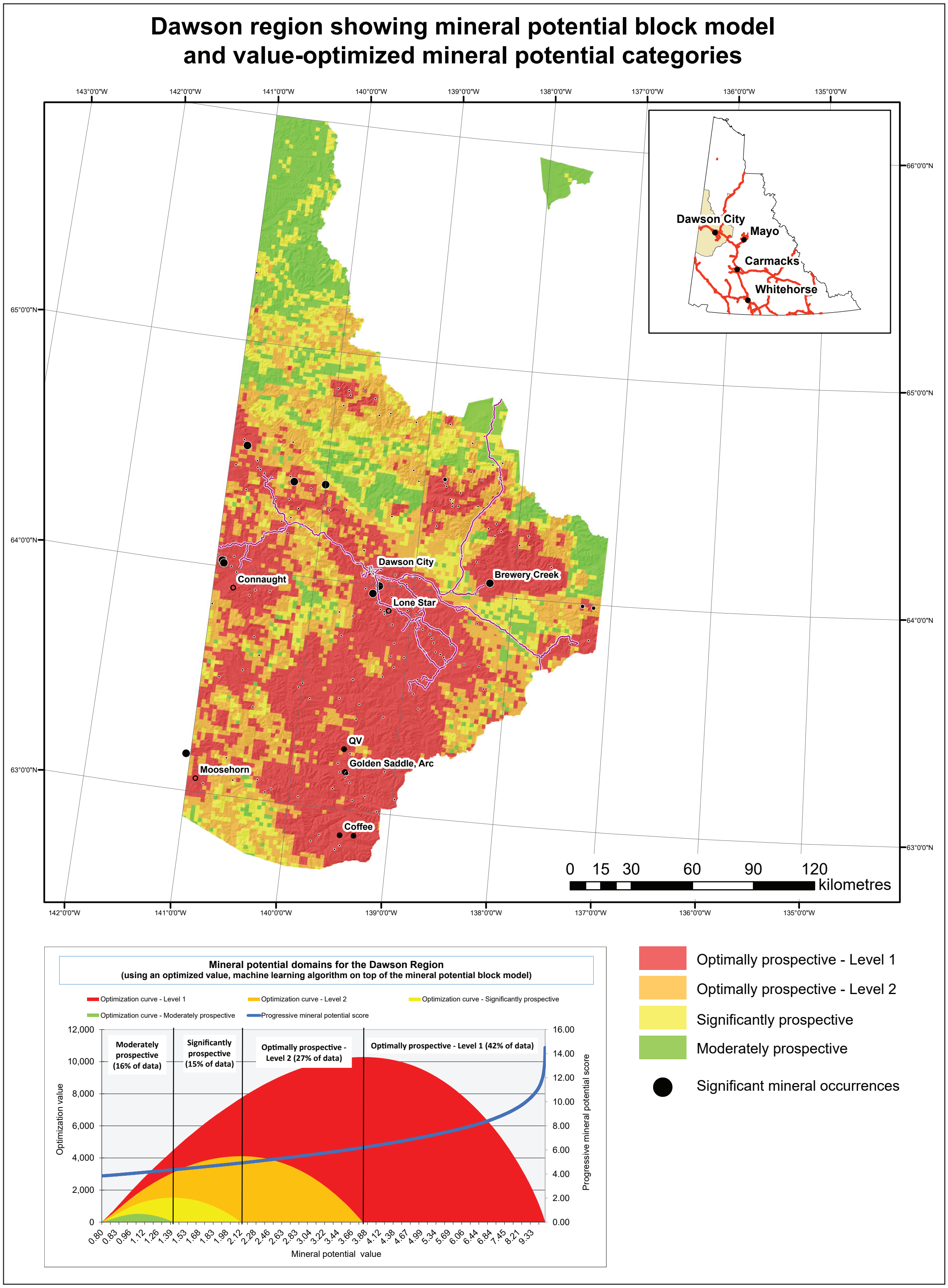

Figure 4. *The value-optimization mineral potential map for the Dawson region. Measures of confidence are excluded for clarity, no smoothing of cell boundaries has been effected.*

6. The expected contribution of each lithological unit in each basin to the drainage sample assay values is calculated using the average lithological “grade” for the area as a whole;
7. The expected sample values for each watershed basin (for the elements of interest) are then calculated;
8. The expected sample values are compared to the actual assay values obtained for each watershed basin; then
9. Anomalous watershed basins at the >97th percentile are identified and separated out.

Categorizing Mineral Potential Confidence

In addition to mineral potential per se, mineral potential maps produced by the Yukon Geological Survey contain measures of bedrock mapping confidence to facilitate land use planning decisions. The confidence metrics distinguish between well-mapped areas that might be deemed highly prospective and poorly mapped areas that might also be rated as highly prospective; or highlight tracts classified as having lower mineral potential due solely to a lack of geological data.

On the Beaver River watershed and Dawson region maps, measures of confidence for non-plutonic rocks were based on the amount of mapping completed (Bullen, 2020), without taking other factors into account, such as the quality and date of the mapping, whether the maps were compiled from a number of earlier unrelated maps or the result of dedicated mapping exercises, scale of mapping, etc. For plutonic rocks, the confidence measures were based on the dating method utilized, and whether whole rock geochemical analyses had been carried out. The confidence measures were deemed to be adequate for land use planning purposes, yet imperfect.

Consequently, a new, more robust, bedrock mapping confidence scheme was devised in the second half of 2020, in close collaboration with Yukon Geological Survey’s bedrock mapping group. The scheme has been applied to mineral potential maps since January 2021. The procedure is described below.

1. The bedrock map for Yukon was broken down into individual map components.
2. For each map component, the following four attributes were determined:
    a. Original scale of mapping;
    b. The year the map was produced;
    c. Whether the map was produced as a dedicated product intended for standalone publication, or was compiled from a series of unrelated map products; and
    d. The confidence in the mapping.

    The first three are data-driven attributes, whereas the last is knowledge-based.

Each attribute is ascribed a factor as shown in Table 2.

Table 2. *Attribute factors for bedrock confidence mapping.*

Attribute	Range	Factor	Rationale
Scale of mapping	1:50 000 to 1:1000	1.50	Large-scale maps provide more mapping detail than smaller-scale maps
	1:150 000 to 1:63,000	1.00	
	1:500 000 to 1:250 000	0.50	
Year of mapping	Post-2000	1.50	Mapping methods and technologies improve over time, as does access
	Between 1980 and 2000	1.00	
	Pre-1980	0.50	
Compilation vs standalone publication	Standalone map	1.00	Maps produced as standalone products are superior to those compiled from maps produced during unrelated mapping exercises
	Compilation	0.25	
Confidence in mapping	3	1.50	A knowledge-based factor which rates the quality of the mapping
	2	1.00	
	1	0.50	

The four factors are summed to give each map component an overall confidence score. The scores for each rock unit within the area of interest are then incorporated into the fishnet grid as described in Bullen (2020). The confidence scores derived using the method described above result in a robust metric against which to assess bedrock confidence.

Miscellaneous Updates

Additional updates to the Yukon Geological Survey's mineral potential mapping methodology include:

1. Revisions to the map legend to account for the new mineral potential categorization methodology described above. The 3 × 3 mineral potential/confidence square has been replaced by a 4 × 3 rectangle to account for the four machine learning-derived mineral potential categories (Fig. 5); and

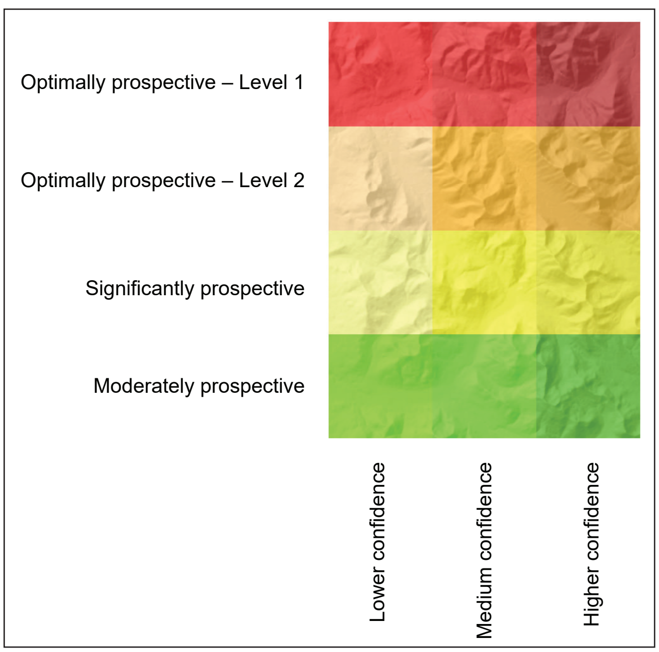

Figure 5. *The mineral potential/confidence graphic from the Teslin mineral potential map revised to incorporate the four machine learning mineral potential categories (the Teslin mineral potential map is not yet in the public domain). In addition, a hillshading underlay has been included to provide a more realistic feel and align with the map itself.*

2. More recently, the map colours have been revised to a multi-hued schema, rather than the red/yellow/green layout used previously. This allows for the production of colour blind-safe maps and also results in output more pleasing to the eye (Fig. 6).

Final Statement

The Yukon Geological Survey has implemented a number of enhancements to the mineral potential mapping process improving the map outputs. These include, *inter alia*, the application of an in-house-derived machine learning algorithm to generate mineral potential categories free of human bias, enhancements to the stream sediment anomaly identification process, a more robust bedrock mapping confidence schema, and improved visual representation. While the mineral potential maps for the Beaver River watershed and Dawson region remain valid in all respects, maps produced in the future will include the new modifications and will resonate better as a result.

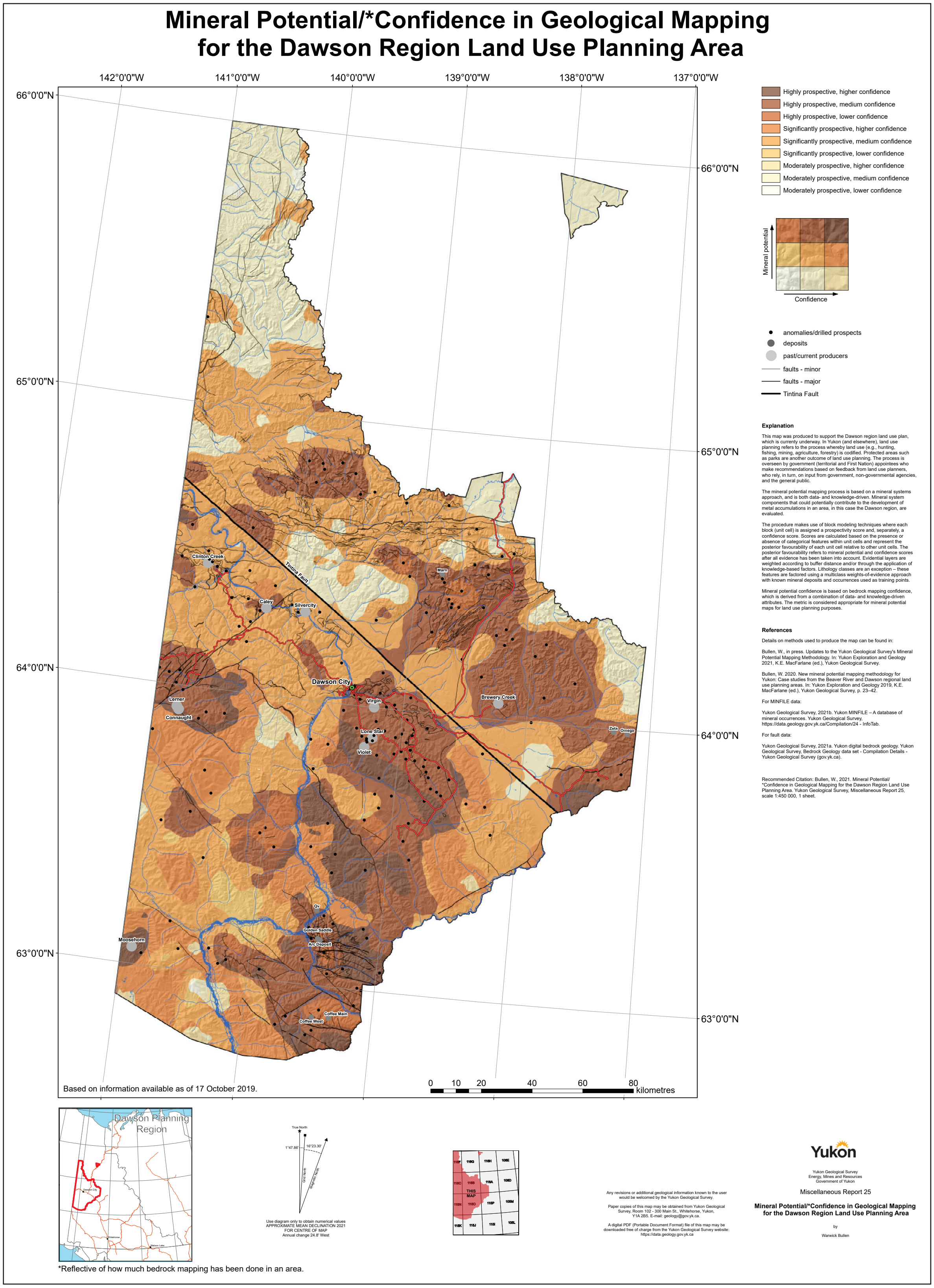

Figure 6. *The mineral potential map for the Dawson land use planning region showing the new multi-hued, colour blind-safe schema.*

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