A DISTURBANCE-SENSITIVITY BASED APPROACH TO PRIORITIZING WATER MONITORING IN NORTHEAST B.C.

1/19/2017

PART 1: REPORT

A Disturbance-Sensitivity Based Approach to Prioritizing Water Monitoring in northeast B.C.

REPORT

Table of Contents

INTRODUCTION

A Disturbance-Sensitivity based (DS) approach has been developed as a tool to support the identification and prioritization of enhanced water monitoring sites across northeast B.C. It summarizes and communicates the status of complex surface water and groundwater systems using a format that is appropriate for water management applications and public understanding. The DS was developed in partnership with the Province, First Nations and stakeholders under the Northeast Water Strategy (NEWS). At three stages throughout its development, First Nations and stakeholder workshops were held in Fort Saint John attended by representatives from: local and regional government; industry including agriculture, oil and gas and mining; nongovernmental organizations; and First Nations. The feedback gained from these workshops was used to develop and evolve the model.

The goal of NEWS is the responsible use and care of water resources through conservation and sustainable practices to ensure human and ecosystem needs are met now and into the future. The DS approach aligns with the NEWS' action area of enhancing information to support decision-making.

Decisions about the location of monitoring stations and the availability of monitoring data affects a broad cross section of people from First Nations to Provincial, local and regional government decision makers and interested stakeholders. As a result, any model that seeks to prioritize monitoring locations needs to be public, transparent, and easily understood in its construction, method and presentation of results. In alignment with NEWS' commitment to enhance public access to water data and information, the DS approach uses publically available data through a Geographic Information Systems (GIS).

METHOD

The DS approach is an Intensity-Weight type of GIS-based assessment where data from variables that represent disturbance (in the case of water quality) or demand (in the case of water quantity) are rated according to their presence (Intensity) in standardized reporting units, and then assigned extra emphasis (Weight) to reflect their relative importance in the determination of risk. By converting data to an intensity measure, it allows for a variety of data types to be combined. The methods employed are parallel to Risk Assessment Model by Mattson and Angermeier (2007), Falcone et al (2010), Danz et al (2007), Paukert et al (2011), Smith et al (2008), Wang et al (2008), Tran et al (2010), and Davies and Hanley (2010).

A simplified example of this model (Figure 1) shows how the total disturbance on a basin is the weighted sum of its component parts. In this example, there are just five stressor layers (modified from Tardiff, 2012). Removing redundancies in the variables set generally produced improves the performance of indices (Falcone et al., 2010).

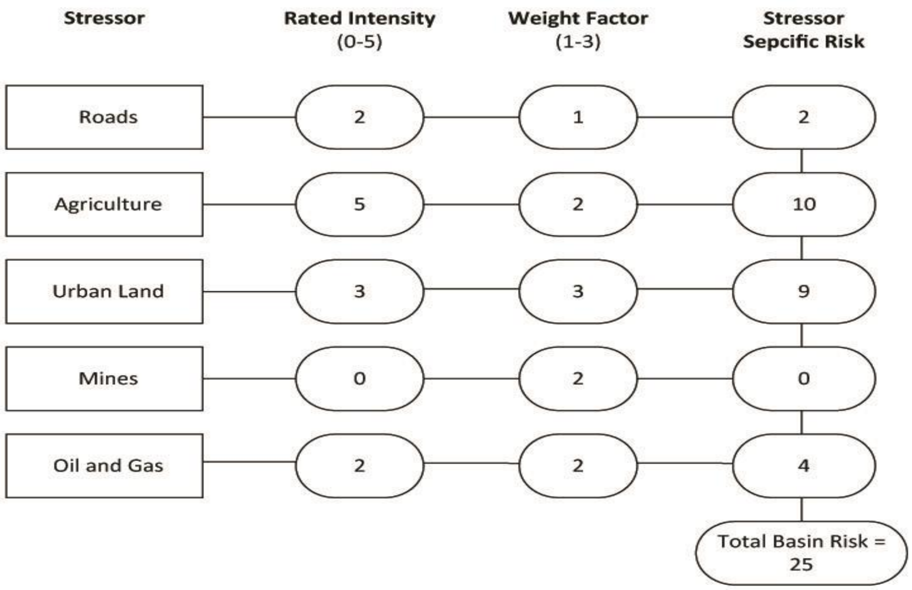

Figure 1. Example of an intensity-weight model (modified from Tardiff, 2012)

To maintain public accessibility, the DS approach used the BC government database of publically available geographically based information to support this modelling. In similar studies, most literature refers to national and regional databases as sources of data with the most common spatial data layers being: land use (urban, crop and pasture land cover), census (human population density), roads, dams, mines, emitting facilities (discharging sites) (Landis and Wiegers, 1997; Mattson and Angermeier, 2007; Danz et al., 2007; Wang et al., 2008; Smith et al., 2008; Bartolo et al., 2008; Falcone et al., 2010; Davies and Hanley, 2010; Paukert et al., 2011).

Data Variables

Two Provincial technical committees were established; one committee for developing the surface water quality and quantity tools and another committee for developing the groundwater quality and quantity tools (committee members listed in the associated Part 2: Data Package). Data and methods were developed collaboratively with interested First Nations and stakeholders through a series of workshops throughout the development of the approach. The technical committees took the feedback from the workshops and led the development of the products. The selection of the data layers were made by consensus. The goal for information layers was that they be: representative of a stressor without being duplicative of each other. Criteria for data selection also necessitated that data are consistent across the study region with good data quality, both in terms of locational accuracy and attributes accuracy. Additionally, in keeping with Provincial Open Government policy, data sources needed to be free and publically accessible. The study used primarily data from the B.C. Geographic Warehouse (BCGW) which is primarily supplied by the Ministry of Forests, Lands and Natural Resource Operations (FLNRO), Ministry of Environment (MOE) or the BC Oil and Gas Commission (OGC). Some national data and a minor component of data from alternate sources supplemented where needed. The data and explicit methods to reproduce results are documented in the companion report labelled Part 2: Data Package (Johnson, 2015).

Data redundancy and spatial scale were considered in selection of variables. Redundancy occurs when the same areas receive extra consideration because of overlapping data sources (e.g., areas of higher population density that overlap areas of urban land cover, areas of higher well density that overlap agricultural development rather than crown land). Spatial scale affects data availability. The finer the spatial scale, the more variables are available, but the data becomes less uniform across the entire region.

Four sets of variables were compiled for northeast B.C. that indicate current and future disturbance from development activity on water quantity and water quality, both for surface water and groundwater. Primary water consumption in the northeast region relates to: oil and gas, 32%; rural domestic and community water supply, 25%; mining, 20%; forestry,16%; agriculture and range, 6%; and road maintenance, 1% (Ministry of Forests, Lands and Natural Resource Operations, 2015). Since road maintenance was nominal, it was disregarded as a major source of disturbance. Table 1 indicates the industries attached to disturbance and the data chosen as being reflective of that disturbance. More detailed data on specific data sets and how it each set was manipulated is available in the companion document (Johnson, 2015). Those four sets of variables were augmented with variables that highlight ecosystems or population areas sensitive to potential effects from disturbance to surface water or groundwater quantity or quality (Table 2).

Table 1: Data Selection for Disturbance

	Source	Surface Water Quantity	Surface Water Quality	Ground Water Quantity	Ground Water Quality
Current Activity	Oil and Gas	Current water demand relative to watershed discharge	Footprint related to infrastructure development including pipelines, well sites, facilities etc.	Water Use for Hydraulic Fracturing by well	Footprint related to infrastructure development including pipelines, well sites, facilities etc.
	Mining	Current water demand relative to watershed discharge	Footprint related to mining activity		Footprint related to mining activity
	Forestry	Current water demand relative to watershed discharge	1. Footprint related to cut blocks less than 20 years old 2. Burn scar area		Footprint related to cut blocks less than 20 years old
	Agriculture	Current water demand relative to watershed discharge	Footprint related to agricultural activities and residential agriculture mixtures		Footprint related to agricultural activities and residential agriculture mixtures
	General	Areas of insufficient	1. Footprint related to roads, railway	1. Groundwater well density	1. Footprint related to roads, railway

		surface water	lines and transmission lines 2. Footprint related to urban built up areas	2. Areas of insufficient surface water	lines and transmission lines 2. Footprint related to urban built up areas
Future Activity	Oil and Gas	Water Use for Hydraulic Fracturing by pool	Areas overlying prospective development areas	Water Use for Hydraulic Fracturing by pool	Areas overlying prospective development areas
	Mining	Footprint related to all leased and licensed areas	Footprint related to all leased and licensed areas	Footprint related to all leased and licensed areas	Footprint related to all leased and licensed areas
	Forestry		Areas of forested crown land		
	Agriculture	Footprint related to agricultural activities and residential agriculture mixtures			
	General			Areas of insufficient surface water	

Table 2: Data Selection for Sensitivity

Area of concern	Surface Water Quantity	Surface Water Quality	Ground Water Quantity	Ground Water Quality
Ensuring water sufficient to meet human needs	Population density	Population density	Population density	DRASTIC model of groundwater susceptibility to contamination
Ensuring water sufficient to meet ecosystem needs	1. Headwater density 2. Lake density	1. Headwater density 2. Lake density		DRASTIC model of groundwater susceptibility to contamination

Intensity

Spatial data for each information variable was transformed into a density or intensity measure. The 'presence' of a variable was normalized by the land area of the reporting unit. For example, a layer of polygon-based agriculture data was transformed into intensity for a surface water model by using total polygonal area of agriculture in a given watershed relative to the total area of that watershed. If agriculture polygons overlapped two watersheds, then the agriculture polygon was divided along the watershed boundary. Point layers were transformed into number or count relative to the area of the reporting unit. Layers with road or pipeline like data were assigned appropriate widths for each segment so a polygonal area per reporting unit could be calculated. Explicit procedures are listed in the companion document (Johnson, 2015).

Reporting units for surface water and groundwater were created by subdividing the region into identified watersheds for surface water and by using 1:50,000 scale National Topographic Service (NTS) map sheets for groundwater (Figure 2).

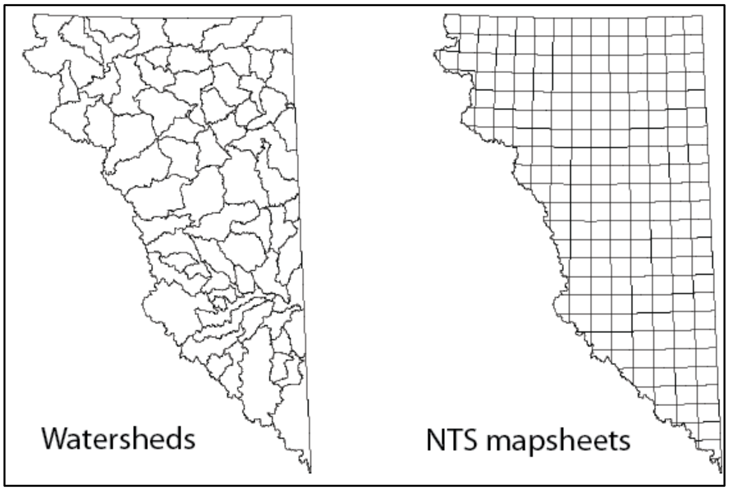

Figure 2. Reporting units for surface water (watersheds; left) and groundwater (NTS map sheets; right).

The spectrum of intensity values for the 69 watershed or 219 NTS map sheets were modified through either standardization or categorization (Table 3). This step was needful so that the various data layers were able to be combined at a later stage. For the range-standard method, the intensity values were normalized between the maximum and minimum values to redistribute the data in a range from zero to one. For the categorization methods, a series of threshold cutoff values used to place the intensity values into bins. Only one method is needed to condition the data but results were generated for several methods in order to choose the most appropriate approach.

Table 3: Summary of intensity rating systems tested

Rating System	Number of categories	Range or Scale	Relative Merits	Examples of Similar Systems
Range standardized	none	(Best) 1 – 0 (Worst)	Pro: Spreads data across a broad range so that there is more discernment of differences. Con: the highest and lowest value may not represent a true high or low, so data can be skewed	Wang et al., 2008; Falcone et al., 2010
Threshold-based by thirds	4	0 → 0 0 < Values ≤ 33rd percentile → 1 33rd percentile < Values ≤ 66th	Pro: Simplifies data and reduces influence of extreme values	Mattson and Angermeier, 2007; Paukert et

		percentile → 2 66th percentile < Values ≤ 100th percentile → 3	Con: coarse generalization of the data	al., 2011
Threshold-based by fifths	5	0 < Values ≤ 20th percentile → 1 20th < Values ≤ 40th percentile → 2 40th < Values ≤ 60th percentile → 3 60th < Values ≤ 80th percentile → 4 80th percentile < Values → 5	Pro: Simplifies data and reduces influence of extreme values Con: generalizes the data; more categories to consider	Falcone et al., 2010
Threshold-based for high disturbance only	5	50 < Values ≤ 60th percentile → 1 60th < Values ≤ 70th percentile → 2 70th < Values ≤ 80th percentile → 3 80th < Values ≤ 90th percentile → 4 90th percentile < Values → 5	Pro: Simplifies data and reduces influence of extreme values; focus solely on areas of intensity Con: generalizes the data; ignores areas with low level disturbance as not a priority for monitoring	Falcone et al., 2010
Binary	2	0 < Values ≤ 0.5 → 0 0.5 < Values ≤ 1 → 1	Pro: Simple method that can produce similar results to more complicated methods Con: generalizes the data such that any degree of subtlety is lost	Paukert et al., 2011

Weighting Data Layers

A secondary reassessment of data layers was done to ensure that one variable isn't over-represented when capturing a category of stress was completed (Smith et al., 2008). This is done by re-grouping the heavily represented variables into one variable by using average value. Falcone *et al* (2010)completed a comparison test of three weighting methods (Chi-squared, χ^2; principle component analysis, PCA; and no weighting) and concluded that weighting the variables is important to the degree that redundancy is present in the final dataset, but it is less important, or even undesirable, if variables have already been well reduced.

For the surface water tools, overrepresentation was avoided by having one layer represent each contributing factor or industry. In many cases several layers were combined into one. For example, disturbance associated with oil and gas infrastructure required combining data layers for well sites, facilities, and pipelines. Explicit procedures are listed in the companion document (Johnson, 2015). For groundwater tools, knowledge is too limited to apply reduction techniques to the data layers either through data layer grouping. Some weighting was applied where warranted by expert opinion.

Imbalances were also be dealt with as part of the weighting process. For this study, weight factors based on expert opinion were assigned independently of a variable's intensity. Weighting helps ensure data layers will represent the magnitude of the potential impact to the environment. This approach is supported by similar studies. Mattson and Angermeier (2007) proposed a structured and rational system to compile expert opinion to determine the importance, or weight, of each stressor variable in the determination of risk. Paukert *et al* (2011) compared results from a weighting system against a no weighing system and concluded that simpler and less subjective risk assessment methods produce similar results to the more complex and subjective methods.

The surface water committee and peer review workshop participants agreed on a simple weighting scheme with 50% of the focus for enhanced monitoring based on current disturbance. The remaining weight was split with 30% weight on areas with higher population or sensitive ecosystems and 20% weight on areas where enhanced monitoring could precede future development activity. In general, the variable layers were weighted equally within those broad categories as seen in the following tables 4-8. Occasionally expert opinion weighted one layer more heavily. For instance, future development in mining, agriculture and oil and gas development is equally weighted for surface water quality (Table 5), but more heavily weighted for future impact on water quantity demand by the oil and gas industry (Table 4).

Table 4: Surface Water Quantity Weighting System for Monitoring

Indicator Layer	Weight		
Future Development • Potential oil and gas consumption • Potential consumption by mining • Potential consumption by agriculture	**20%**	**20%**	12% 4% 4%
Current Demand versus Supply • Water allocation relative to mean annual discharge • Restrictions on Surface Water use	**50%**	**50%**	35% 15%
Sensitivities **Rural and domestic water use** • Population	**30%**	**15%**	15%
Aquatic ecosystem sensitivity • Wetland density per watershed • River headwater density per watershed • Lake density per watershed		**15%**	5% 5% 5%

Table 5: Surface Water Quality Weighting System for monitoring

Indicator Layer	Weight		
Future Development **Land tenure** • Oil and Gas • Mining • Forestry	**20%**	**20%**	8% 8% 4%

Current Development	**50%**		
Land disturbance		**35%**	
• agriculture			5%
• forestry - clear cuts			5%
• forest burn areas			5%
• municipal / urban			5%
• oil and gas infrastructure			5%
• linear projects			5%
• mining			5%
Waste discharge permits		**15%**	
• Sewage - total discharge / annual runoff			7.5%
• Industrial - total discharge / annual runoff			7.5%
Sensitivities	**30%**		
Rural and domestic water use		**15%**	
• Population			15%
Aquatic ecosystem sensitivity		**15%**	
• Wetland density per watershed			7.5%
• Headwater River density per watershed			3.75%
• Lake density per watershed			3.75%

The first groundwater quantity assessment (Table 6) identifies areas for enhanced ambient monitoring of quantity primarily a function of industrial activity. The second groundwater quantity assessment (Table 7) uses data about areas of potential abundant water supply to indicate areas enhanced well information from monitoring wells, private wells, geology or geophysics would provide valuable targets for aquifer characterization efforts. For groundwater quality, similar to surface water quality, the assessment considers current and future industrial activity as well as environmental sensitivity (Table 8). The groundwater committee tried various approaches but in the end, in conjunction with feedback for peer review workshops, the best approach was considered one that mirrored the surface water process. Groundwater quality is prioritized equally across various possible disturbances because there is little information with which to weight indicator layers. The DRASTIC indicator layer is weighted more heavily because it considers sensitivity; the ability for a contaminant to infiltrate through the soil horizon and enter groundwater.

Table 6: Groundwater Quantity Weighting System Based on Demand

Indicator Layer	Weight
Future Demand • Potential water use Oil and Gas	5%

Current Demand • Density of Water Wells and Source Wells • Surface Water Restrictions • Water used for hydraulic fracturing in Oil and Gas • Mining Tenure • Population	25% 25% 15% 15% 15%

Table 7: Groundwater Quantity Weighting System Based on Productivity

Indicator Layer	Weight
Supply **Development indications** • Yield from water wells, source wells and springs	55%
Natural Resource indications • Surficial Geology • Aquifer Size • Paleovalleys	15% 15% 15%

Table 8: Groundwater Quality Weighting System Based on Vulnerability

Indicator Layer	Weight
Future Development • Unconventional Gas Play • Mining Tenure	7% 7%
Current Disturbance • Agriculture • Forest clear cuts • Urban development • Oil and Gas - wells • Oil and gas - facilities • Oil and gas - pipelines • Linear – transmission lines • Linear – Roads • Linear – Rail lines • Active mines	7% 7% 7% 7% 7% 7% 7% 7% 7% 7%
Sensitivities • Potential Groundwater vulnerability to contamination – DRASTIC	16%

Once the data was divided into reporting units, classified according to intensity and weighted according to importance, the data was summed by reporting unit. The results were ranked for the 69 watersheds and 219 NTS map sheets. The results were categorized by percentile into thirds.

Comparison of Intensity Rating Systems

To compare intensity rating systems, the ranks generated in all five systems (range standardized, X1; threshold-based by thirds, X2; threshold-based by fifths, X3; threshold-based for high disturbance only, X4; and binary, X5) were compared for each of the 69 basins. An average rank for each basin was assigned based on the average of the five rating system results. Basins were sorted according to the average rank and then assigned a new rank based on the order of the 69 basins. This new rank was taken to be the dependent variable 'Y'. A regression was generated between the each system rating (X1 – X5) and Y. Each of the regressions was detrended to generate the remainders. The remainders were summed into bins (0-9, 10-19, 20-29, 30-39, 40-49, 50-59, and 60-69).

RESULTS

Weighting System

The surface water committee tested several weighting systems including: 1) range standardized; 2) threshold-based by thirds; 3) threshold-based by fifths; 4) threshold-based for high disturbance only; and 5) binary. Since there is no absolute measure available for the amount of disturbance or the sensitivity of a basin, the ranking results were compared with each other using the average of the five rankings (Figure 3 and Table 9). Three of the rating systems generated very similar results: threshold-based by thirds; threshold-based by fifths; and threshold-based for high disturbance only. Ninety percent of the rankings these three systems assigned to a basin were within 10 places or less than average ranking from all five systems. The range standardized system was substantially differently than the other systems in rankings. From a qualitative perspective, the binary and threshold-based by thirds systems were the easiest to comprehend quickly and intuitively. As a result, the threshold-based by thirds rating system was chosen for this project. It is not as good as the threshold-based by fifths for high disturbance only system, but it provides generally the same results and is far simpler to execute and understand.

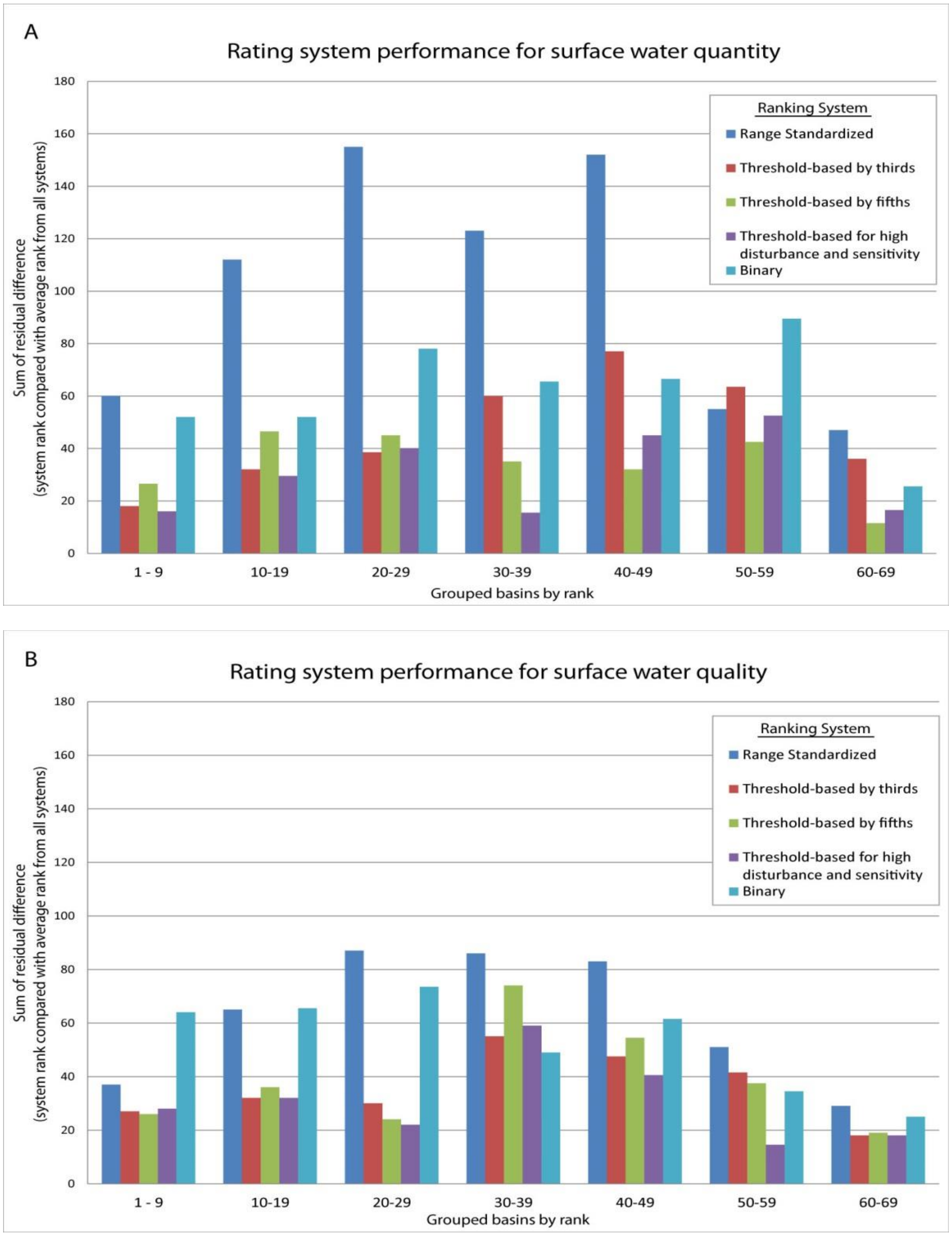

Figure 3. Comparison of five intensity rating systems for (a) quantity and (b) quality in surface water basins. For each system a linear regression was run against the average basin ranking. The remainders were summed. The lower the sum of the remainders, the better that rating system approximates the average.

Table 9: Performance comparison of five intensity rating systems

	Range Standard -ized	Threshold -based by thirds	Threshold -based by fifths	Threshold-based for high disturbance and sensitivity	Binary
Quantity - Sum residual difference	704	325	239	215	429
Percent basins over 10 ranking points different than average	42%	10%	3%	1%	25%
How representative is the rating system for surface water quantity? (1 = results are similar to average, 5 = results are very different from average)	5	3	2	1	4
Quality - Sum residual difference	438	251	271	214	373
Percent basins over 10 ranking points different than average	17%	4%	4%	3%	20%
How representative is the rating system for surface water quantity? (1 = results are similar to average, 5 = results are very different from average)	5	2	3	1	4
How difficult is the rating system to implement? (1=simple, 5= complicated)	5	2	3	4	2
How intuitive is the rating system? (1=clear, 5= obscure)	5	1	3	4	1

Prioritization of Basins for Surface Water Monitoring

For surface water quantity and quality monitoring (Figures 4 and 5), the 69 basins were classified according to the threshold-based by thirds intensity rating system and weighted according to tables 4 and 5 respectively. The individual data layers and their associated intensity ratings are presented in Appendices A and B for surface water quantity and quality respectively. The results for ranking surface water quantity and quality are available in Appendices F and G. These models are generated to prioritize basins in need of monitoring, so it is important that the results be presented in conjunction with the location of current monitoring efforts.

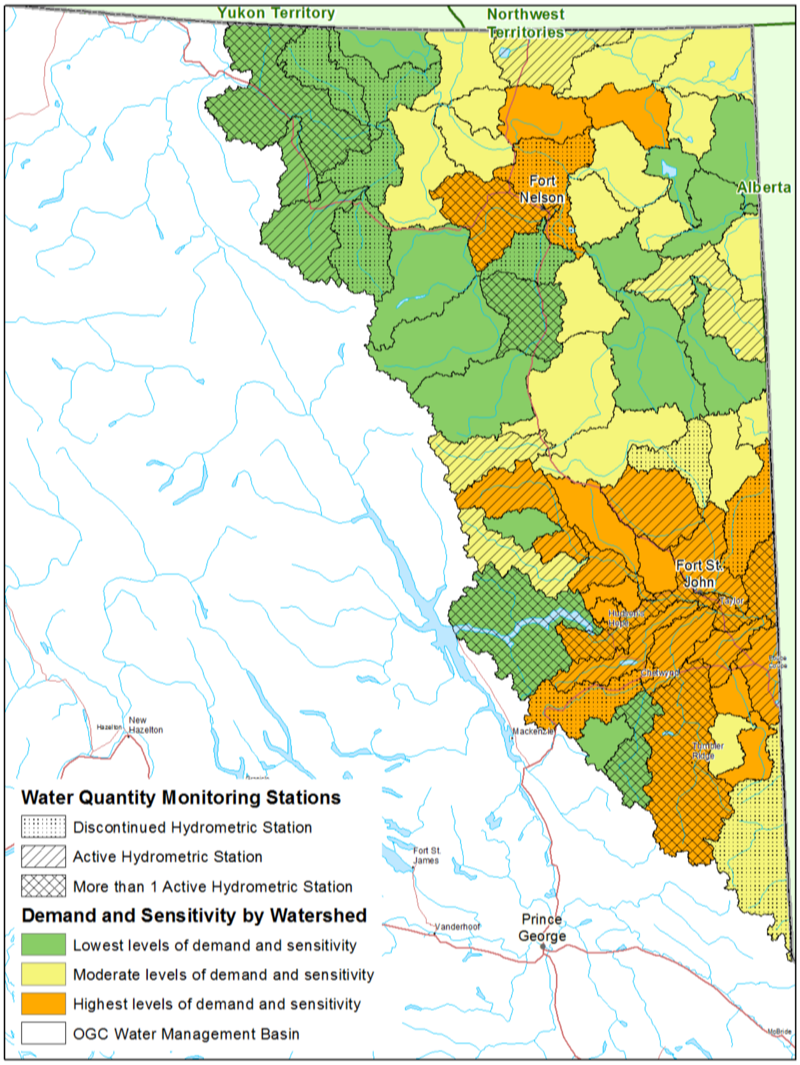

Figure 4. Prioritized basins in Northeast BC for surface water monitoring of quantity. The comprising data layers are in Appendix A. The relative rankings for each watershed are available in Appendix F.

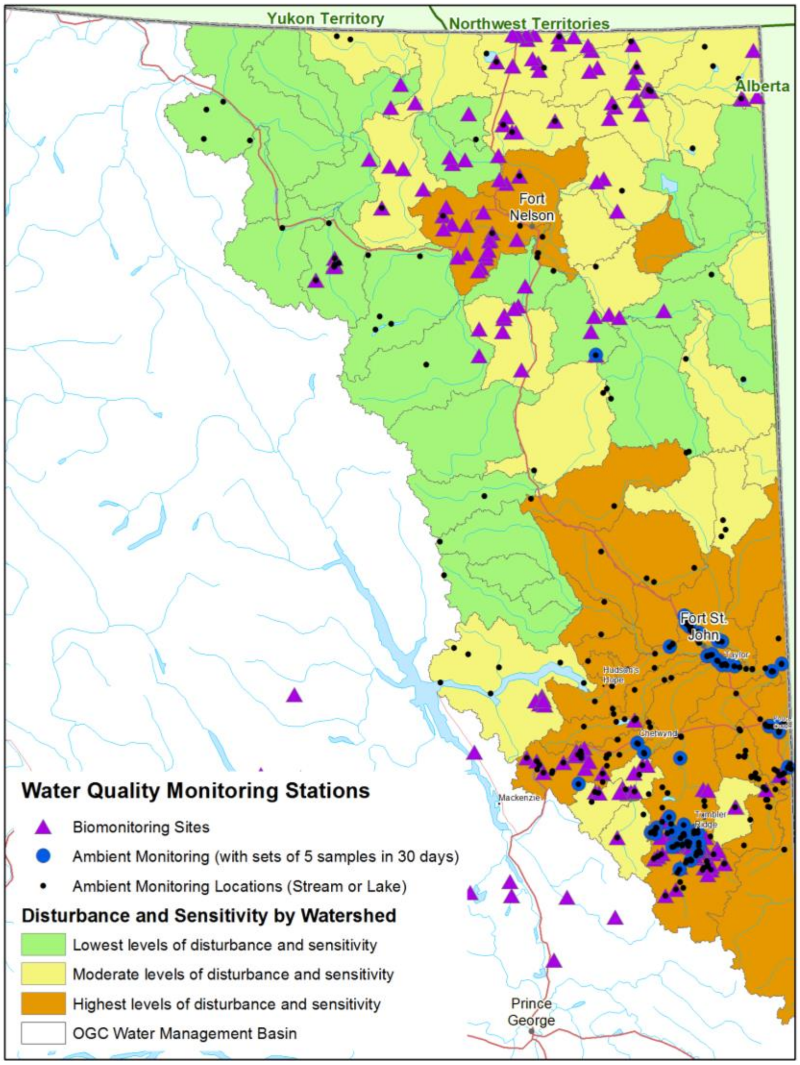

Figure 5. Prioritized basins in Northeast BC for surface water monitoring of quality. The comprising data layers are in Appendix B. The relative rankings for each watershed are available in Appendix G.

For prioritizing groundwater quantity monitoring by demand, for regional supply characterization (Figure 6 and 7) or for prioritizing groundwater quality monitoring (Figure 8), the 219 NTS map sheets were classified according to the threshold-based by thirds intensity rating system and weighted according to tables 6, 7 and 8 respectively. The individual data layers and their associated intensity ratings are presented in Appendices C, D, and E respectively. The results for ranking groundwater quantity and quality are available in Appendices H and I.

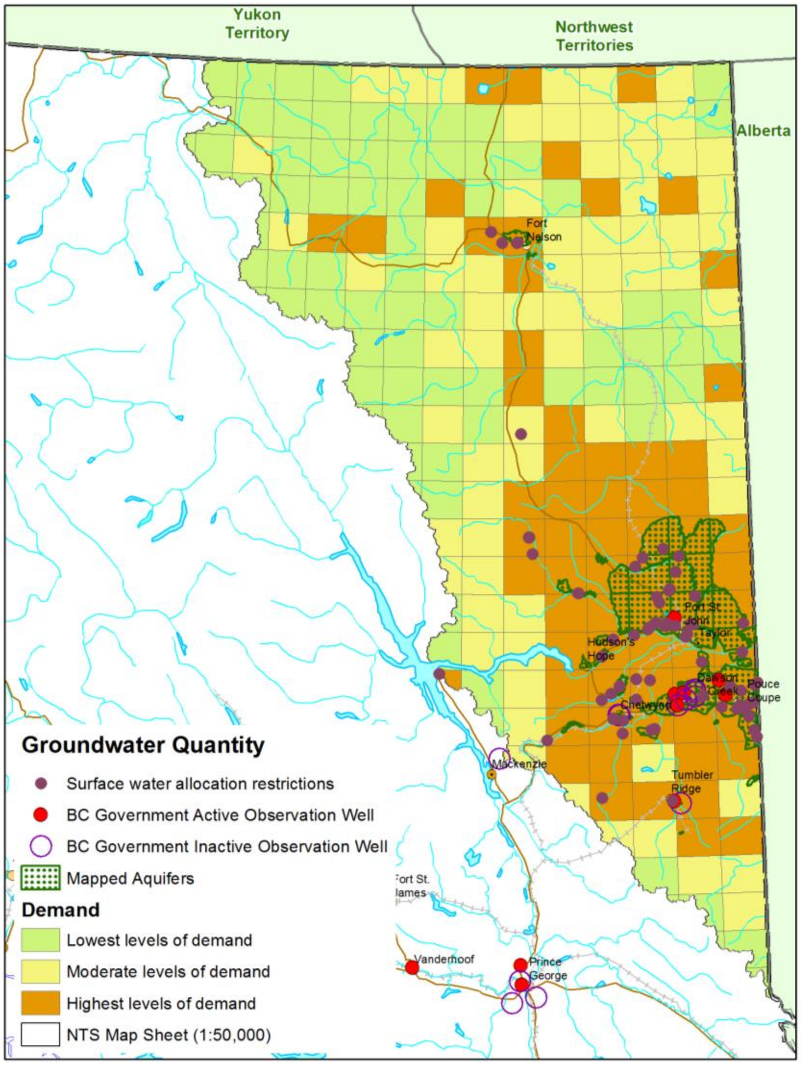

Figure 6. Prioritized NTS mapsheets in Northeast BC for groundwater monitoring of quantity on the basis of demand. The comprising data layers are in Appendix C.

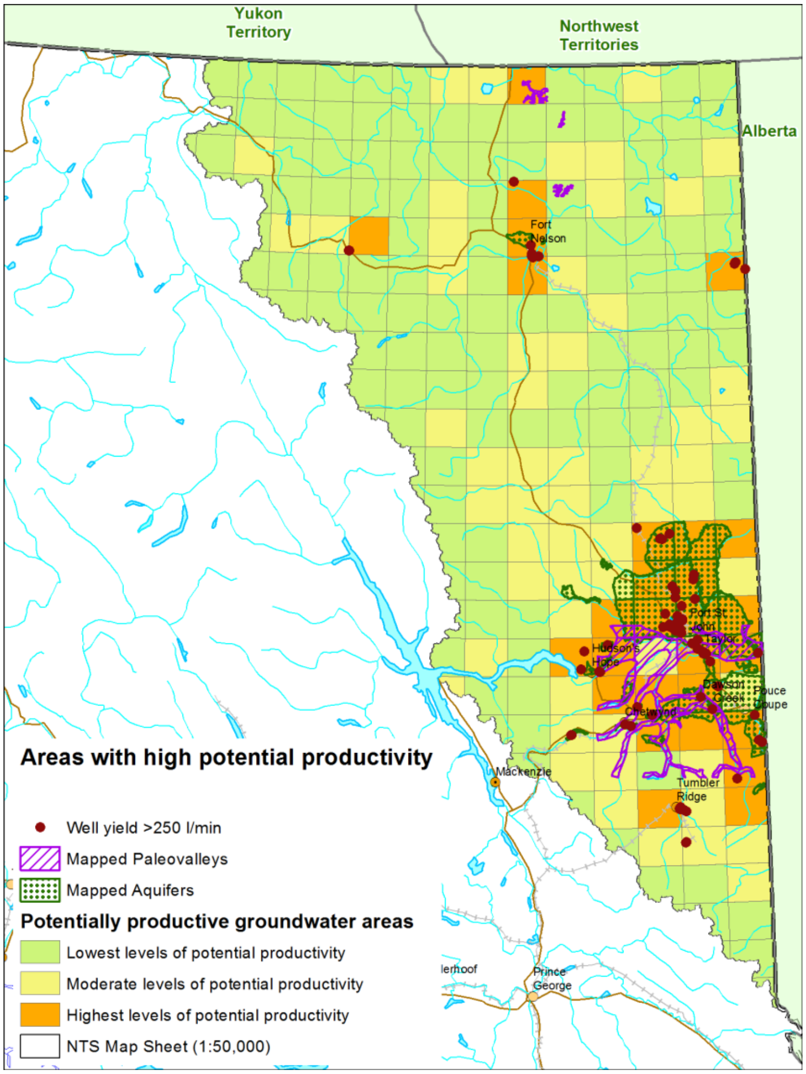

Figure 7. Prioritized NTS mapsheets in Northeast BC for where there is potential producibility from groundwater flow systems. The comprising data layers are in Appendix D.

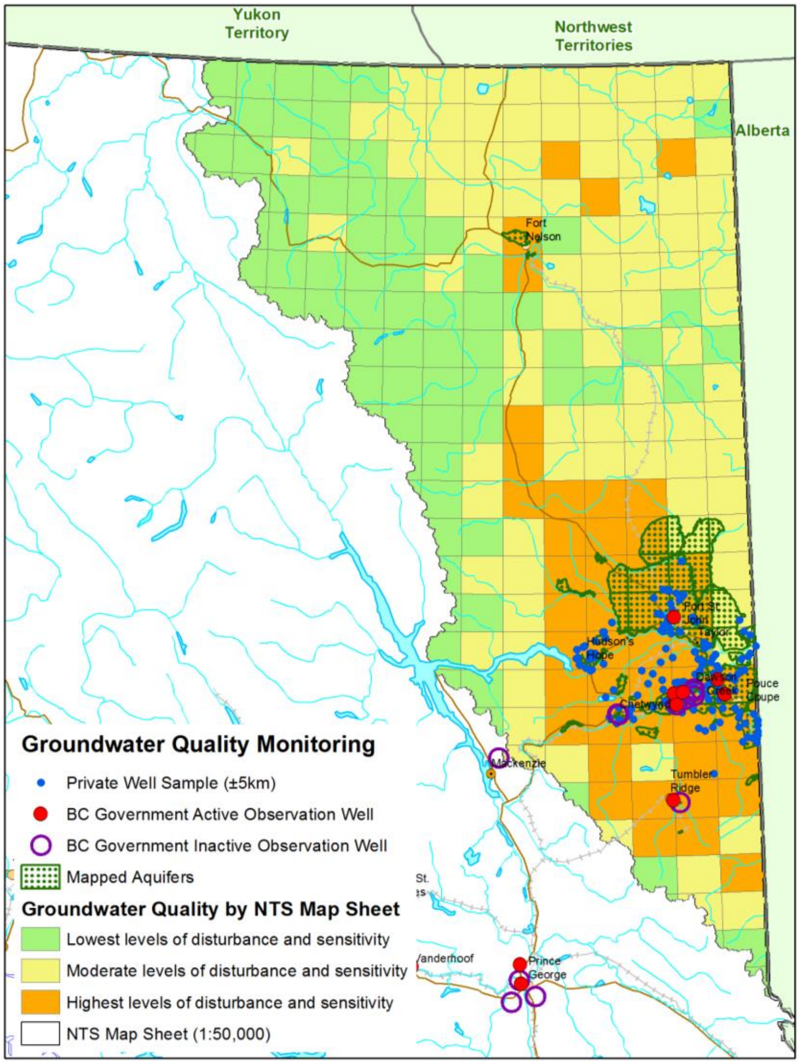

Figure 8. Prioritized NTS mapsheets in Northeast BC for groundwater monitoring of quality. The comprising data layers are in Appendix E.

DISCUSSION

Improvements to the method

Most of the approaches to modelling cited in the introduction do not consider upstream-downstream spatial relationships with the exception of Paukert et al (2011). Paukert *et al* (2011), while computing the intensities per reporting unit for downstream watersheds, included the stressor variables for that downstream watershed plus the stressor variables from upstream watershed(s) and considered the reporting unit to be the combination of the downstream and upstream watershed(s). Then, the risk indices for the combined upstream-downstream watersheds were assigned to the downstream watersheds (Figure 9). This method was not employed here but was actively considered by the surface water committee.

It was considered too labour intensive for the initial tool development but is recommended for incorporation in future work.

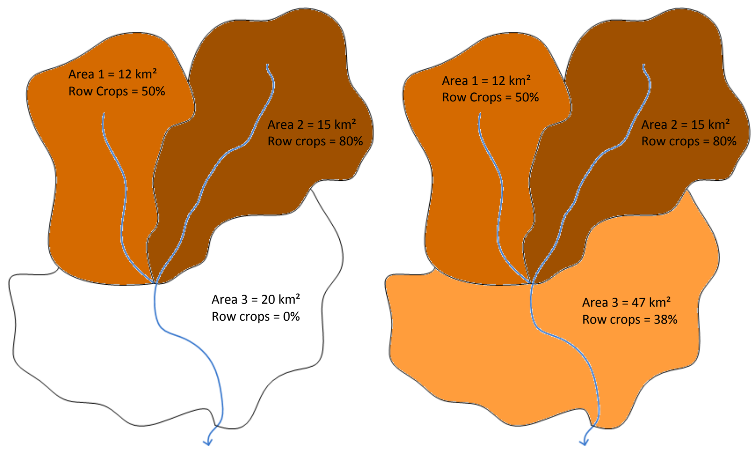

Figure 9. Example of stressor intensity per basin. Most models don't integrate upstream stressors in downstream basins (left), however it can be incorporated like Paukert *et al* (2011) (right).

Surface Water

The DS tool for surface water quantity (Figure 4) indicates that watersheds in the Peace River region and those around the City of Fort Nelson have the highest monitoring needs based on current and future water demand by industry, environmental sensitivity and population based constraints. These results were congruent with the expert opinions of the surface water committee. When the need for monitoring is compared with the location of monitoring stations in the Provincial network, more than half of the watersheds in the highest disturbance and sensitivity category have active hydrometric monitoring (Table 10). However a third of the watersheds have had no monitoring. This tool is useful for planning enhanced monitoring and regionalization models.

Table 10: Surface water quantity monitoring in basins with the highest level of disturbance and sensitivity

Watershed	Intensity rating for basins with the highest level of demand and sensitivity	Total hydrometric stations	Active hydrometric stations
Pouce Coupe River	2.73	5	1
Lower Pine River	2.63	1	1
Cache Creek	2.58	0	0
Lower Beatton River	2.54	4	1
Lower Kiskatinaw River	2.53	1	1
Murray River	2.39	4	3
Lower Halfway River	2.39	2	1
Blueberry River	2.38	1	1
Lower Peace River	2.36	4	3

East Kiskatinaw River	2.34	0	0
Middle Fort Nelson R.	2.30	2	0
Lower Muskwa River	2.21	2	2
Lynx Creek	2.21	0	0
Cameron River	2.19	0	0
Middle Kiskatinaw River	2.12	0	0
Doig River	2.04	1	0
Upper Peace River	1.94	2	2
Moberly River	1.92	1	1
Tsea River	1.91	0	0
Kiwigana River	1.91	0	0
Upper Halfway	1.87	2	1
Upper Pine River	1.87	2	0
Farrell Creek	1.82	0	0

The DS tool for surface water quality (Figure 5) was similar to that of surface water quantity indicating that watersheds in the Peace River region and those around the City of Fort Nelson have the highest monitoring needs based on current and future water disturbance by industry, environmental sensitivity and population based constraints. Again, these results were congruent with the expert opinions of the surface water committee. Existing monitoring is more difficult to indicate. Unlike water quantity measurements with hydrometric stations, water quality can be assessed by a water grab sample and can be heavily impacted by the sample location relative to sewage outfall, industrial development etc. Additionally, water quality can vary widely over time. It is considered good procedure to revisit the same site at least 5 times within a 30 day period to show reproducibility in water analyses. The sampling sites indicated above are for ambient monitoring and those sites meeting the 5 samples in 30 days protocol are flagged. The monitoring site is only reflective of upstream conditions, so monitoring sites near the outflow for the 69 watersheds are more reflective of the overall condition of the watershed. There are few watersheds where this is the situation.

Additionally, the province has partnered with environment Canada in using biomonitoring to assess water quality. A biomonitoring program requires a baseline model to be established for comparison purposes. A Canadian Aquatic Biomonitoring Network (CABIN) model has been constructed for most areas of BC including, most recently the Liard Watershed area of northeast BC. Biomonitoring is still required in order to build a CABIN model for the Peace Watershed. The absence of biomonitoring stations in the Peace Region is noticeable in Figure 5.

Groundwater

Groundwater quantity is prioritized by demand in Figure 6. Sensitivity is not included as a factor here because there is no strong GIS indicator layer that would indicate human or ecosystem sensitivity from exigent groundwater withdrawal. Surface water restrictions are weighted fairly heavily because in areas where surface water is restricted, it is expected that groundwater will be used to meet that demand. The highest demand is in the Peace Region and Montney gas play area. Population centers like Fort Nelson, Dawson Creek, Hudson Hope, Tumbler Ridge and Pouce Coupe are also considered high demand areas. Mapped aquifers only cover a small component of northeast BC but the mapped areas and observation wells coincide with high demand areas.

As there are large areas yet to be mapped with respect to groundwater in northeast BC, a priority decision support for characterization of the groundwater flow systems was generated (Figure 7). Areas in the Montney play and near the city of Fort Nelson have higher priority because knowledge about wells with greater yield, and the prospect of paleovalleys and large aquifers indicates these areas result in information about large groundwater flow systems.

Areas of higher groundwater vulnerability are prioritized in Figure 8. The highest levels of disturbance and sensitivity are in developed areas and where mapped aquifers are vulnerable to surface related contamination. The Peace Region and near the City of Fort Nelson are in the highest category. Monitoring wells have been installed in the area around Dawson Creek and geochemical sampling of private wells in the Peace Region is providing some information about groundwater quality. Areas north of Fort St John have little monitoring of water quality.

Gathering information to characterize groundwater is expensive and information collection surveys tend to be deployed around large groundwater flow systems with greater potential to meet water demand. These information collection surveys include sampling water from private wells, monitoring wells, geological studies and drill holes and regional airborne, ground-based and downhole geophysics. Prioritization of areas for groundwater characterization can be considered through a process that combines both demand and potential productivity. The combined ranking of groundwater demand and potential productivity provides prioritized locations for information collection surveys. The results are presented in Figure 10 and are available in Appendix H. Much of the active information survey work and groundwater characterization is already occurring in the most needful areas. More characterization work is needed near Fort Nelson, Tumbler Ridge and the areas around Blueberry River and Halfway River.

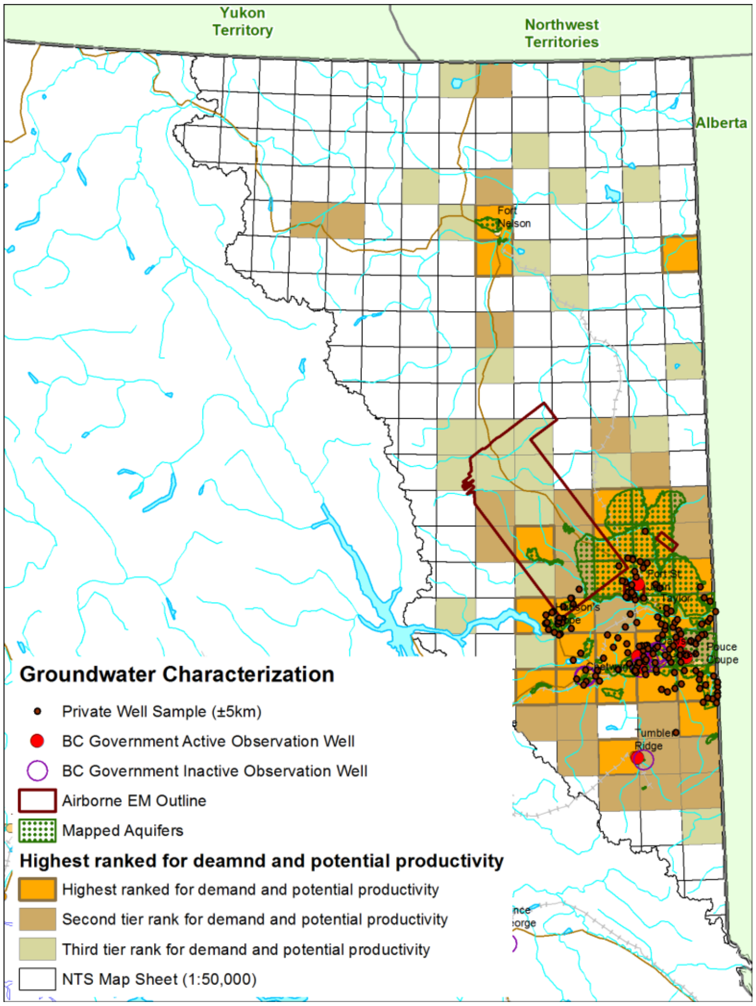

Figure 10. Prioritized NTS mapsheets in Northeast BC for groundwater characterization. The rankings for groundwater demand and potential productivity were combined. This map shows those mapsheets with the highest combined priorities. The relative rankings for each mapsheet are available in Appendix H.

Since groundwater monitoring requires a single well for both water quality and quantity monitoring, monitoring prioritization can be considered through a combination of both vulnerability and demand. The results for the combined ranking of groundwater demand and vulnerability are available in Appendix I. Figure 11 shows the combination of the highest priority areas for demand and for vulnerability for only the map sheets in the top third of their respective DS assessment. The resultant map indicates a need for monitoring near all the population centers in Northeast BC and also in the industrially active zone just north of Fort St. John along the Halfway, Blueberry and Beatton Rivers. Several monitoring wells have already been installed near Dawson Creek.

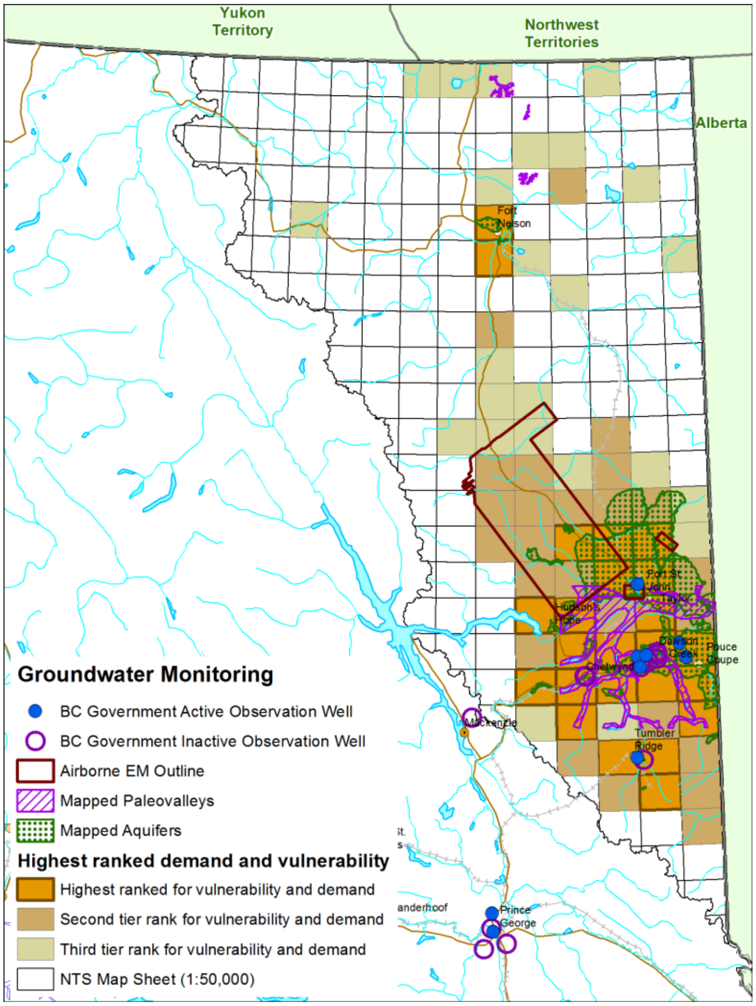

Figure 11. Prioritized NTS mapsheets in Northeast BC for groundwater monitoring. The rankings for groundwater vulnerability and groundwater demand were combined. This map shows those mapsheets with the highest combined priorities. The relative rankings for each mapsheet are available in Appendix I.

SUMMARY AND IMPLICATIONS

The DS tools for surface water quantity and quality are designed as a preliminary ranking tool to help prioritize a series of watersheds for enhanced monitoring and characterization. The DS tool for surface water quantity has been used to support discussions for enhanced surface water monitoring in the Peace Region. Two watersheds with the highest levels of disturbance and sensitivity and with no monitoring were targeted for monitoring; the East Kiskatinaw River and Lynx Creek. The DS tool for surface water quality has highlighted a need for more broad scale characterization of surface water quality reflective of larger watersheds. This prioritization exercise supports continued development of biomonitoring for the construction of the CABIN model in the Peace Region. Many watersheds in the highest category for disturbance and sensitivity are in need of water quality monitoring.

The DS tools for groundwater demand, characterization and vulnerability are helpful but provide more utility when used in combination to consider areas for groundwater characterization (Figure 10) or groundwater monitoring (Figure 11).

REFERENCES

Bartolo, R., van Dam, R. and Bayliss, P. (2008): Chapter 3 - Semi-quantitative risk assessments – The Relative Risk Model; *Bartolo, R.; Bayliss, P.; van Dam, R.*, Ecological risk assessments for Australia's Northern Tropical Rivers, Sub project 2 of Australia's Tropical Rivers – an integrated data assessment and analysis (DET18). A report to Land & Water Australia. Environmental Research Institute of the Supervising Scientist. Darwin, NT. National Center for Tropical Wetland Research, pages 164–270. URL <http://www.environment.gov.au/system/files/resources/054092c1-5bff-4149-abd9-93b27747e55d/files/triap-sp2-chapter-3.pdf, [12/9/2014].

Danz, N.P., Niemi, G.J., Regal, R.R., Hollenhorst, T., Johnson, L.B., Hanowski, J.M. et al. (2007): Integrated measures of anthropogenic stress in the U.S. Great lakes basin; *Environmental management,* Volume 39, Issue 5, pages 631–647, DOI: 10.1007/s00267-005-0293-0.

Davies, H. and Hanley, P.T. (2010): 2010 State of the Watershed Report. Saskatchewan Water Authority. Regina, SK.

Falcone, J.A., Carlisle, D.M. and Weber, L.C. (2010): Quantifying human disturbance in watersheds: Variable selection and performance of a GIS-based disturbance index for predicting the biological condition of perennial streams; *Ecological Indicators,* Volume 10, Issue 2, pages 264–273, DOI: 10.1016/j.ecolind.2009.05.005.

Johnson, E.G. (2015): Disturbance-sensitivity based approach: Part 2: Data package. Ministry of Forests, Lands and Natural Resource Operations. Victoria, B.C.

Landis, W.G. and Wiegers, J.A. (1997): Design considerations and a suggested approach for regional and comparative ecological risk assessment; *Human and Ecological Risk Assessment: An International Journal,* Volume 3, Issue 3, pages 287–297, DOI: 10.1080/10807039709383685.

Mattson, K.M. and Angermeier, P.L. (2007): Integrating human impacts and ecological integrity into a risk-based protocol for conservation planning; *Environmental management,* Volume 39, Issue 1, pages 125–138.

Ministry of Forests, Lands and Natural Resource Operations (2015): Northeast Water Stategy. Victoria, B.C. URL <http://www2.gov.bc.ca/gov/DownloadAsset?assetId=036CAF38B8DC439492702F9C11C7A3FB&filename=2015-northeast-water-strategy.pdf>.

Paukert, C.P., Pitts, K.L., Whittier, J.B. and Olden, J.D. (2011): Development and assessment of a landscape-scale ecological threat index for the Lower Colorado River Basin; *Ecological Indicators,* Volume 11, Issue 2, pages 304–310, DOI: 10.1016/j.ecolind.2010.05.008.

Smith, E.R.,Mehaffey, M.H.,O'Neill, R.V.,Wade, T.G.,Kilaru, J.V. and Tran, L.T. (2008): Guidelines to Assessing Regional Vulnerabilities. United States Environmental Protection Agency. Washington, DC. URL <www. EPA.gov>.

Tardiff, G. (2012): Literature Review – Risk-based Basin Assessments.

Tran, L.T., O'Neill, R.V. and Smith, E.R. (2010): Spatial pattern of environmental vulnerability in the Mid-Atlantic region, USA; *Applied Geography,* Volume 30, Issue 2, pages 191–202, DOI: 10.1016/j.apgeog.2009.05.003.

Wang, L., Brenden, T., Seelbach, P., Cooper, A., Allan, D., Clark, R. and Wiley, M. (2008): Landscape based identification of human disturbance gradients and reference conditions for Michigan streams; *Environmental monitoring and assessment,* Volume 141, Issue 1-3, pages 1–17, DOI: 10.1007/s10661-006-9510-4.