Developing a Priority Matrix to Expand Water Monitoring in the Upper Canadian Columbia Basin

Steps for Pilot Implementation

M. Carver and G. Utzig June 23, 2021

On June 8th 2020, Living Lakes Canada convened a hydrology workshop (2020 Hydrology Workshop) to develop recommendations for a phased expansion of the water-related monitoring network in the Upper Columbia Basin (UCB). The workshop was a culmination of effort over multiple years[1] to initiate a collaborative approach for water monitoring in the UCB. In particular, the workshop focused on evaluating a proposal for setting monitoring priorities within a scientific framework. The foundation of the proposed scientific framework begins with stratification of the UCB into ten hydrologic regions (HRs), reflecting broad variations in UCB climate (CBT 2017, see Figure 1 and Table 1). Within the HRs, the monitoring network takes into account the full range of variation of potential watershed response, while also emphasizing watersheds critical to biodiversity conservation, community sustainability, and ecosystem resilience in the face of climate disruption. The concept of the "water balance" forms the basis for evaluating the functional aspects of individual watersheds within the HRs.

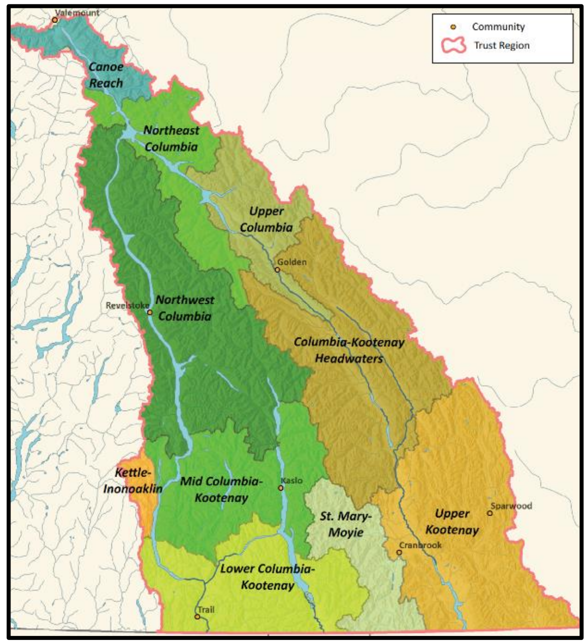

Figure 1. UCB hydrologic regions as indicated by patterns of climate and surface runoff.

Table 1. Relative climate across the UCB's hydrologic regions.

Hydrologic Region	Climate Overview
Canoe Reach	Moderate moist summers, cold moist winters with moderate snowpacks
Columbia-Kootenay Headwaters	Warm moist summers, cold dry winters with moderate snow packs at higher elevations
Kettle-Inonoaklin	Very hot dry summers, mild winters with moderate-to-low snowpacks. Transitional to regions west of the Basin.
Lower Columbia-Kootenay	Hot dry summers, moderately cool winters with moderate snowpacks at higher elevations
Mid Columbia-Kootenay	Transitional between Northwest Columbia and Lower Columbia-Kootenay
Northeast Columbia	Warm wet summers, cold wet winters with deep snowpacks
Northwest Columbia	Moderate wet summers, wet cool winters with deep snowpacks
St. Mary-Moyie	Transitional between Lower-Columbia Kootenay and Upper Kootenay
Upper Columbia	Warm moist summers, cold wet winters with moderate snowpacks at higher elevations
Upper Kootenay	Very dry to moist hot summers, cold dry winters with low-to-moderate snowpacks

[1] This initiative began with a 2017 conference hosted by Living Lakes Canada entitled *Water Data Hub Cracking the Code (in 3-D) An Open Source Data Dialogue towards a Columbia Basin Water Monitoring Framework*.

It is recognized that to develop a complete UCB Priority Monitoring Matrix, key knowledge and information additional to the water balance approach is required. These components are shown in Figure 2 where First Nations and local, regional and provincial government priorities are included along with those of watershed stewardship groups and industrial water users.

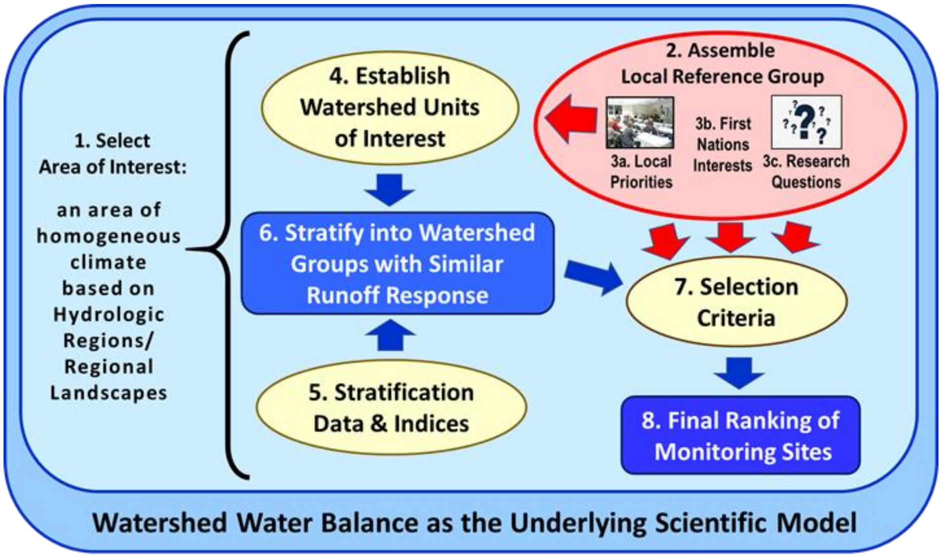

Figure 2. Underlying basis and steps for the implementation of the monitoring strategy.

Figure 3 summarizes the approach as a step-by-step framework to identify and select monitoring sites for the pilot areas chosen:

1. Select an area of interest for implementation of the pilot project.
2. Assemble Local Reference Group to provide local knowledge, and set context for planning.
3. Determine local priorities for expanded monitoring through preliminary discussions with the Local Reference Group to assemble an inventory of existing monitoring and a preliminary gap analysis.
4. Establish watershed units of interest to be characterized by the monitoring and confirm the boundaries in discussions with the Local Reference Group.
5. Create database of watershed characteristics and indices for assessment using GIS layers such as water features, a digital elevation model, bedrock mapping, and stream flow data.
6. Stratify watershed units of interest statistically to identify groups that respond similarly so that monitoring results from one watershed in a group are relevant to others in that group.
7. Return to the Local Reference Group to establish selection criteria based on logistics and local priorities for ranking candidate watersheds in each group for new monitoring.
8. Estimate installation and operational costs based on location, stream size, parameters, accessibility and local volunteer availability. Finalise network by evaluating costs against present and projected budgets, rankings from step 6 and need for phased implementation.

The initial implementation of this framework is on a pilot basis or “test case” and allows for evaluation and iterative refinement of the process as challenges are encountered and solutions found. The long-term objective is to expand the monitoring network to eventually cover representative locations across the UCB. Once operational, additional monitoring data from the expanded network should be assessed and analyzed on an ongoing basis to identify potential adjustments in the network.

This document lays out the detailed steps required to implement the framework within a selected UCB area or “areas of interest.” Water monitoring can and does require significant resources. As significant portions of the Basin evolve to a more semi-arid state and as extreme events increase in frequency, a comprehensive, scaled and nested approach to monitoring will help to build the economies of scale required for increased cost efficiencies to collect data sets necessary to better anticipate drought and flood impacts. Data are required for decision makers to support efforts to address community and ecosystem adaptation options while we still have them.

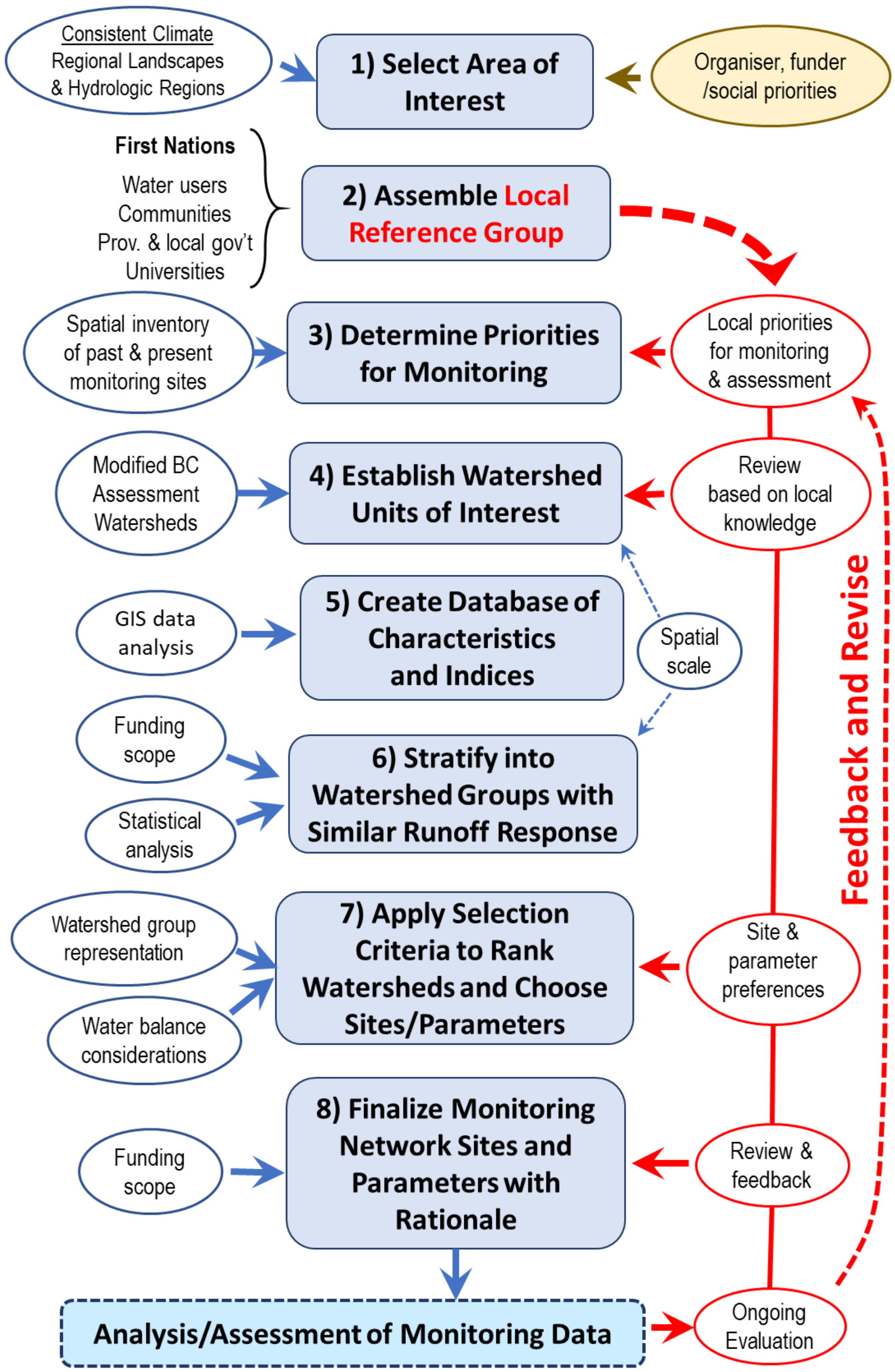

Figure 3. Overview of the framework and the inputs required at each step.

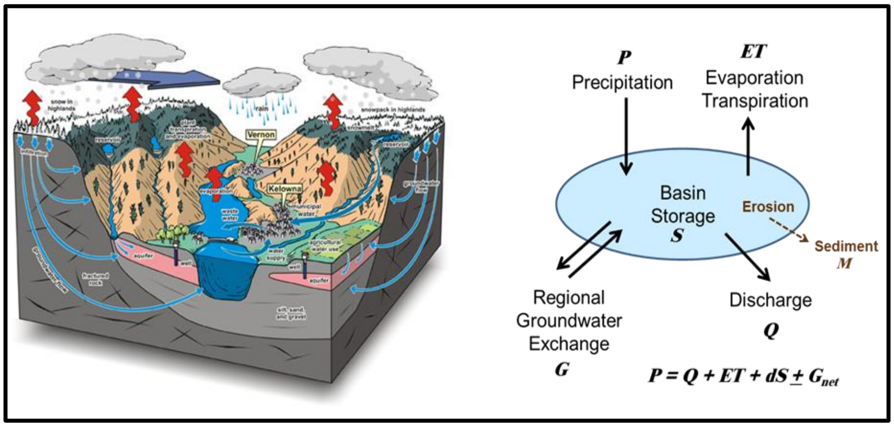

Figure 4. The water balance equation as a concept to represent the functional exchanges of water within a watershed.

Water Balance Concept

As introduced above, the concept of the water balance provides the underlying scientific model for organizing proposed monitoring. The left side of Figure 4 provides an example of watershed complexity as it exists in nature, and the right side demonstrates how water balance analysis simplifies that complexity into measurable quantities of water fluxes over time. It is used here because much of the variation in watershed behaviour is associated with the water balance and its components are of great relevance to society's needs. Although erosion and sediment transport are not direct factors in the water balance, they are included here as they are often of significant interest in relation to watershed response.

STEP 1: SELECT AREA OF INTEREST

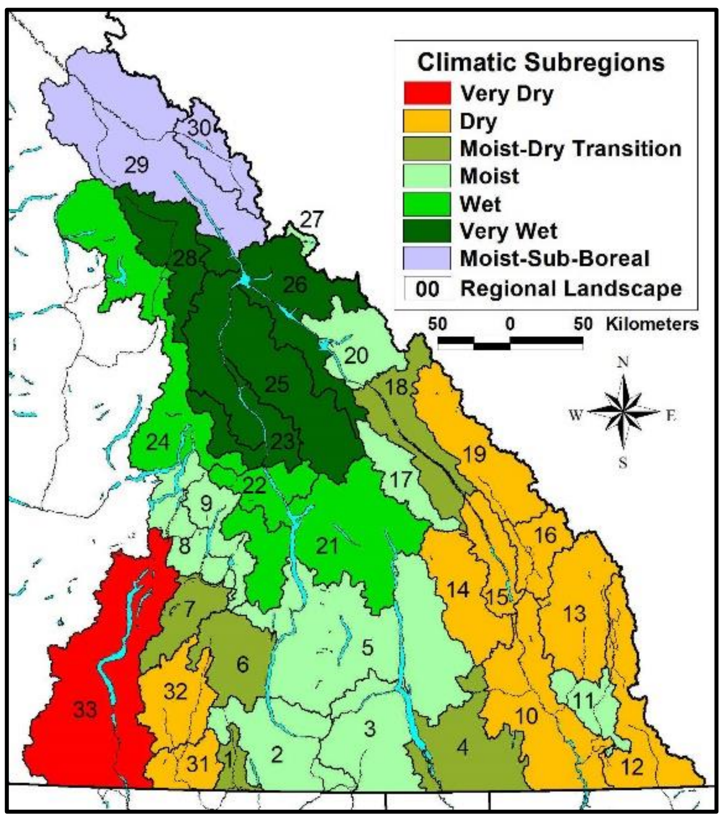

Figure 5. Regional landscapes of southeastern BC, including the UCB (Utzig 2019).

The lead organization will have to decide on an "area (or areas) of interest" for implementation of the pilot project. The framework is predicated on the selection of an area that has a relatively uniform climate, employing that as the initial regional stratification criterion. If funding and resources are available, it may be desirable to select two contrasting areas for pilot projects (*e.g.*, one East and one West Kootenay), however, the need for climate uniformity would still apply to each area.

With additional effort, the selection decision could be supported by supplementary scientific information. For example, GIS layers of relevant variables across the entire UCB could be assembled in this step ahead of further work. Some analysis of these layers would be carried out to determine preferred areas of interests based on additional criteria related to successful testing – e.g., a full or manageable range in each factor under consideration. Although pursuing this option would lengthen the process of this pilot application, it should also reduce the time required later when full application of the approach is implemented and may help to better identify any revisions that might be needed.

Organizing the monitoring network according to HRs provides a foundation for the overall design, rooted in contrasting regional climates. The HRs have been derived by grouping "regional landscapes" (RLs) into a higher classification that conforms to regional watershed boundaries (Utzig 2019). RLs are areas within which climate envelopes are relatively uniform within elevation bands across the unit (see Figure 5).The workshop's application of the preliminary approach utilized a HR that is also a single RL (Mid Columbia-Kootenay HR and RL5), but the approach can also be applied at the level of a smaller RL or groups of similar RLs. This increased spatial resolution provides a stronger linkage to the patterns in hydrologic response which drive the network design.

Within these areas of similar climates and patterns of runoff, "watershed units of interest" will be identified in subsequent steps based on landscape patterns and scales appropriate to meet local information needs. Watersheds across spatial scales provide the primary units on which the design of the monitoring network will be structured in the analysis. Watersheds have highly complex behaviour exhibited in terms of water, sediment and nutrients fluxes. To resolve additional variation in behaviour, groupings of watersheds are organized around a water balance foundation – essentially an accounting of the inflows, storage and outflows of water at different spatial scales. See Figure 2. The potential for complementary groundwater monitoring may also influence the selection of an area of interest.

STEP 2: ASSEMBLE LOCAL REFERENCE GROUP

Once an area of interest is selected, a Local Reference Group is established to provide local knowledge, and set the context for planning. The Local Reference Group includes First Nations, water users, water managers, local watershed interests, appropriate technical expertise (*e.g.*, hydrology, fisheries, terrain/soils) drawn from local and provincial government staff, consultants and/or university researchers. Emphasis is placed on involving individuals with first-hand knowledge of the area of interest, while at the same time ensuring that the range of values and interests is represented. Although some groups may choose not to actively participate, it is important to invite all relevant groups.

The Local Reference Group is a source of local knowledge about the area of interest, such as: watershed histories, occurrence of past extreme events, water demands, past watershed impacts from development, current and past water monitoring, sources of existing data, access, *etc*. The Local Reference Group is also a source of information on potential local groups who may be interested in participating in monitoring activities and/or individuals who may be interested in paid work and/or volunteering in monitoring activities.

The Local Reference Group is consulted throughout the process to ensure that decisions are consistent with local on-the-ground conditions. Its members are there to provide information on local needs and priorities, and to ensure that the final selection of monitoring sites and parameters will meet local needs.

STEP 3: DETERMINE PRIORITIES FOR MONITORING

Undertake preliminary discussions with the Local Reference Group to determine local priorities for expanded monitoring. Engage individuals with knowledge related to priority values of local watersheds (*e.g.* high water demand, high-value aquatic habitat) and significant risks to those values (flood risk to homes or infrastructure, areas proposed for development, low-flow issues, *etc*.). Solicit local perspectives on changes to streamflow that may have happened in recent years in relation to climate disruption, water withdrawals, and any other factors considered important locally. Future water withdrawals may be highly responsive to periods of scarcity and, as such, they should be considered carefully for monitoring in order to understand their contributions in future water budgets. To support these preliminary discussions, assemble, and provide GIS data, as needed, such as:

- water license locations and volumes
- flood hazard mapping over-laid with infrastructure locations
- aquatic habitat – locations, values and vulnerabilities
- locations and types of past incidences of extreme events related to streamflow
- aquifer data - boundaries, types, groundwater levels

Although increased baseline monitoring is a fundamental benefit of almost any expanded monitoring network, proposed monitoring should be focused on answering key questions. Many of these questions would involve components of the water balance. Which variables most directly answer the key questions? How will responses to the questions be quantified using the monitoring data? Which variables can be monitored most efficiently and which responses can be assessed most effectively? During the planning phases, every attempt should be made to have proposed monitoring go hand-in-hand with assessment. Preliminary ideas on criteria for incremental build-out of the network may also be envisioned in the planning stages based on the range of potential outcomes from the new monitoring data.

Based on CBT (2017) and on the detailed summary of monitoring sites provided in Carver (2019), create a preliminary spatial and tabulated inventory of past and present water monitoring sites and data within the area of interest. Update this inventory based on best information available through the Columbia Basin Water Hub[2], Pacific Climate Impacts Consortium Data Portal[3], the Kootenay Boundary Water Tool[4], and other sources such as BC ministries. Engage the Local Reference Group to further update the inventory. The Columbia Basin Water Hub may be of particular value to the Local Reference Group due to its wide range in datasets including water quantity and quality, groundwater levels, wetland monitoring, snow surveys, glacier studies, reports, images and various other forms of knowledge and information. Using this information, prepare an inventory of existing monitoring and a preliminary monitoring gap analysis based on local knowledge and perspectives. Using this compilation, identify where appropriate monitoring sites are already in place and where good long-term data sets are available. Given the length of time generally required for new sites to generate valuable insights, it is important before selecting new sites to take the time to establish where target data already exist and to some degree, how additional data can also complement existing networks.

[2] https://livinglakescanada.ca/project/columbia-basin-water-hub/
[3] https://data.pacificclimate.org/portal/pcds/map/
[4] https://kwt.bcwatertool.ca/watershed

STEP 4: ESTABLISH WATERSHED UNITS OF INTEREST

Within the area of interest, individual "watershed units[5] of interest" need to be defined. Watershed units of interest are areas that will be characterized by monitoring and are shown by boundaries within the area of interest. The provincial Assessment Watersheds (AWs) provide the best off-the-shelf starting point (Carver and Gray 2010). They will require initial modification in at least two ways based on what is readily known:

- Identify appropriate nested and aggregated watersheds (building on the AWs) to address spatial-scale requirements of the future network (*e.g.* larger watersheds that may contain multiple AWs).
- Where smaller watersheds have significant values, especially those that are contained in face units (residual areas) of the AWs, there may be a need to map additional watersheds not present in the AW coverages.

With initial revisions to AWs complete, a preliminary Watersheds Units of Interest map requires review by the Local Reference Group to ensure consistency with local context and to capture all the watersheds with local concerns, major values and opportunities for potential research projects. Based on review comments, revise and finalize Watershed Units of Interest map.

STEP 5: CREATE DATABASE OF WATERSHED CHARACTERISTICS AND INDICES

Once the watersheds of interest have been identified with the area(s) of interest, assemble GIS layers of relevant variables for assessment. It is conceivable that for social or logistical reasons, the work's promoter may determine that it is preferable to go forward with two different areas of interest.

The following are GIS data layers and other information required for the area of interest in order to characterize and classify the watershed units of interest:

- BC water data: streams, lakes, wetlands, aquifers, glaciers, watershed boundaries at 1:20:000
- Digital elevation model: topographic mapping, TIN slope mapping, aspect mapping for PET assessment, potential hydrologic flow mapping (potential for use in modeling slope stability and surface erosion hazards), LiDAR if available
- Bedrock mapping – re-classify based on types appropriate for assessing the presence of karst and degree of jointing, bedrock topography (resulting from or to infer overburden thickness) and where terrain/soil mapping is unavailable potentially use bedrock mapping to model soil texture for use in assessing potential storage and sediment sources
- Terrain/soil mapping: re-classify with regard to infiltration and storage capacity (using texture and depth); use as inputs to mapping for stability and surface erosion hazards (using texture and moisture regime)

[5] Although the approach is applied here to watersheds only, the area of interest can be supplemented by designating specific waterbodies of interest for monitoring (*e.g.*, lakes or aquifers). This would expand the initial focus of the pilot exercise to include components of the water balance additional to streamflow, making the effort more complex. However, an expanded scope would provide opportunity to explore additional issues associated with a wider range in monitoring parameters. Selection of these additional waterbodies would require additional criteria.

- Vegetation Resource Inventory (forest cover): calculations of Equivalent Clearcut Area and evapotranspiration; can be complemented by BEC zone and TEM/PEM mapping
- Streamflow data and groundwater levels, both current and historic: where available, collate data from the Kootenay Boundary Watershed Tool, the Living Lakes Canada Water Hub and/or BC's Aquarius Time-Series database.
- Climate data: gather from relevant climate stations, snow courses and gridded information from ClimateBC

By overlaying these GIS coverages with the watershed units of interest, create a database of characteristics for each of the proposed watershed units, including the determination of indices and descriptors listed in Table 2.

STEP 6: STRATIFY WATERSHED UNITS OF INTEREST USING STATISTICAL ANALYSES

This step involves grouping the watershed units of interest based on understanding of their behaviours as interpreted from their characteristics and watershed indices. The full range of watershed units of interest across a study area is stratified into Watershed Groups likely to have similar flow regimes and responses to a changing climate and/or disturbance. The approach uses variation in these factors, or surrogates for these factors, as the primary criteria for stratification of watersheds. The basic assumption is that watersheds with similar expressions of these characteristics will likely respond in similar ways, and monitoring results from one watershed in a group can be extrapolated to other watersheds within that group. Groupings can be established with statistical methods that group and differentiate among populations. For example, cluster analysis and discriminant analysis and other procedures can be used to group individuals in a population based on a weighted selection of characteristics. The watersheds may have to be stratified by size prior to analysis in some cases.

It is important in this step to know the scope of available funding and the sites currently being monitored. With this information, the statistical analyses can be used to identify the number of groupings that would allow monitoring of at least one watershed in each Watershed Group.

STEP 7: APPLY SELECTION CRITERIA AT LOCAL LEVEL

Results from the stratification work provide a starting point for understanding the variation within a region. In this step, the focus returns to the Local Reference Group to establish selection criteria based on their logistics and priorities in order to decide and potentially rank which watersheds in each group are candidates for new monitoring. Ensuring that all relevant groups, including First Nations, continue to be involved in the Local Reference Group is essential at this stage. If some members of the Local Reference Group have had to pull back for their own reasons, be sure to maintain a flow of information to update them and periodically restate the invitation to participate.

Table 3 lists examples of selection criteria for consideration in this step. It includes incorporating First Nations' priorities, identifying a range of community priorities related to natural hazards, and a collection of factors related to making the proposed network as efficient and cost-effective as possible. Elaboration of many of these selection criteria (and more) will be provided directly by the Local Reference Group. The funding scope of potential new monitoring is included in this step to help the Local Reference Group gain perspective in their prioritization recommendations.

Table 2: Watershed groupings, characteristics and indices used as stratification criteria and their links to basic water balance components.

Item	Definition or Role/Purpose	Water Balance[1]					
		P	Q	S	ET	G	M
Watershed Groupings							
Hydrologic Regions[2]	• broad-scale representation of regional climate tied to large watersheds	•			•		
Regional Landscapes[2]	• finer subdivision of regional climates • provide higher degree of homogeneity of regional climate	•			•		
Size	• classification as provided in BC's Assessment Watersheds[2] (starting point)		•				
Type	• classes to ensure homogeneity of watershed groupings • examples: major, nested, residual, *etc*.,		•				
Watershed Characteristics							
Glaciers	• affect seasonal flow distribution and sediment production		•				•
Wetlands	• support low flows and buffering of floods • have conservation value		•				•
Lakes	• affect sedimentation, stream nutrient status, and flow regime		•		•		•
Bedrock	• affects permeability, hydrologic response and potential sediment production • examples: intrusive, sedimentary, metamorphic, calcareous		•	•		•	•
Surficial materials	• directly affects hydrologic response (through storage) and potential sediment production • need to estimate material texture/depth and distribution (1:50,000 soil/terrain mapping)			•			•
Vegetation	• affects snowmelt, evapotranspiration, and hydrologic response • typical classes: non-vegetated, alpine, forested, grassland, *etc*		•		•		
Watershed Indices							
Drainage Density	• ratio of stream length to area affects peak flow response		•				
Hypsometric Integral[3]	• ratio of upper and lower elevation areas • provides elevational weighting affecting distribution of precipitation and snow	•					
Aspect index	• distribution by slope and elevation • affects snowmelt and evapotranspiration		•		•		
Circularity Ratio	• ratio of watershed area to a circle with the same perimeter • correlates with size and duration of peak flow		•				
Relative relief	• ratio of relief to area • correlates with sediment production						•
Melton Ruggedness	• ratio of relief to perimeter • correlates with sediment production/transport						•
Topographic Wetness Index	• ratio of contributing area within watershed to total area • used to refine groundwater recharge potential		•	•		•	
Available Water Capacity	• . quantifies water available for groundwater recharge		•	•		•	
Index of channel instability	• consider generalized risk based on slope characteristics (*e.g.*, wetness, hillslope/channel gradients, materials) • correlates with sediment production						•
Channel type	• classes to be developed • affects flow regime (*e.g.*, bedrock vs alluvial)		•				•

1 – See schematic in Figure 2. P-precipitation; Q-discharge; S-storage; ET-evapotranspiration; G-groundwater; M-sediment
2 – See text for reference and further discussion
3 - Also - Hydrometric Index.

A feasible long-term network build-out must be formulated in general along with clarification of the short- and mid-term funding available to get started. Past and present sites (step 3) are reviewed, along with the parameters being monitored. Although proposed monitoring parameters are focused on those related to the water budget, other parameters of interest to First Nations and stakeholders such as water quality metrics, water temperature, and wetland-related information should be considered to grow support for the network. Integrated scientific and practical discussions take place and incorporate potential research priorities such as the impacts of disturbance or climate change. Scientific questions that may drive site selection, for example, may include pairing watersheds with differing levels of road construction and/or forest harvesting. Extent of community volunteer support may also be considered here.

Local concerns and knowledge, the many practical considerations, and funding constraints and opportunities are all brought to bear in the selection of monitoring sites and parameters in light of the Watershed Groups established in step 6. Logistical issues such as ease of access and availability of appropriate monitoring sites will also impact final site selection. These discussions culminate in the selection and ranking of specific watersheds for installation of monitoring equipment and determination of monitoring parameters for each site, recognizing the need to make tradeoffs among valid but competing outcomes.

Table 3. Potential selection criteria when choosing among potential monitoring sites.

Selection Factor	Explanation of Selection Criteria
Indigenous sites	First Nations sites can be of importance and/or a priority for a wide range in cultural, social, spiritual and other reasons
Local sponsors	Shared interests can enable increased monitoring scope and program durability
Nesting of watersheds	Strategically nesting smaller monitored drainages within larger ones can provide information efficiently at a range of scales
Complementarity with existing monitoring	Avoiding duplication with existing monitoring networks creates efficiencies
Access	Access requirements and logistics need to be carefully weighed because of cost implications and may be best known locally
Sediment issues	Fine and coarse sediment plays central role in domestic water consumption, aquatic habitat, safety (*e.g.,*debris flood/flow), and other water-related values
Fisheries significance	Fisheries habitat is widespread but variable; many watershed have streams with high fisheries values
Water-use significance	Concerns about low flows and seasonal water availability can be critical because water use for domestic, industrial, and irrigation purposes may sustain communities/economies
Flooding potential	Many communities have flooding concerns, particularly those situated on alluvial fans
Degree of disturbance	Wildfire, forest harvesting (distribution and percentage), road density, etc. shape the condition of streamflow and other watershed resources
Geographic distribution	A wide distribution of sites is preferred but may require tradeoffs

STEP 8: FINALISE NETWORK IN LIGHT OF BUDGET

The final step involves gathering cost estimates to establish and run individual monitoring stations according to their location, stream size, range/type of monitored parameters, accessibility, availability of local volunteer assistance, *etc*. This information is then used in light of the rankings of step 6 and evaluated against present and projected budgets to develop a Priority Monitoring Matrix to be used in determining the proposed monitoring network. Depending on the nature of funding, the network may be laid out for implementation on a phased basis. Before establishing this matrix as the outcome of the entire process, return to Local Reference Group with rationale for its final review and feedback.

Although beyond the scope of this document, the water monitoring data accumulating from the expanded network should be reviewed in an adaptive and ongoing learning program of data analysis and assessment. Criteria established in the planning phase, and new and revised criteria developed based on current information, should be applied to the data on a frequent basis to assess the value of the established sites and to help evaluate potential further network expansion should additional funding become available. In addition, the proposed approach to monitoring does not replace effective resource management and biodiversity conservation. Additional investigations (management, research, modeling, *etc*.) will be required to build on this monitoring and support adaptive management in addressing typical objectives associated with ecosystem management (*e.g.*, development of environmental flow needs) and community resilience (*e.g.*, water supply/demand planning).

REFERENCES

Carver M 2019. *Water Monitoring and Climate Change in the Upper Columbia Basin - Guidance Information for Planning Monitoring Programs*. Report prepared for the Columbia Basin Trust, 26 p. Available at: https://storage.googleapis.com/wzukusers/user-34247081/documents/ecd402d64c99436790858a84aaf2e0be/Carver_2019_Water%20Monitoring%20Recommendations%20CBT.pdf

Carver, M and M Gray 2010. *BC Assessment Watersheds for Regional Level Applications*. Streamline, 13(2) Spring 2010, p 60-64. Available at: http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=3979B86FD2494FD0A3111669992BCF9B?doi=10.1.1.634.7150&rep=rep1&type=pdf

Carver M and G Utzig 2020. *An Online Workshop: Expanding the Water Monitoring of Canada's Upper Columbia Basin (UCB)*, 51 p. Available at: http://livinglakescanada.ca/wp-content/uploads/2020/10/LLC-wm-wkshp_prcdngs-final_Oct-08-2020.pdf

Columbia Basin Trust (CBT) 2017. *Water Monitoring and Climate Change in the Upper Columbia Basin, Summary of Current Status and Opportunities*. Prepared by Dr. Martin Carver, 61 p. Available at: https://ourtrust.org/wp-content/uploads/downloads/2017-02_Trust_WaterMonitoring-ClimateChange_Web.pdf

Utzig G 2019. *Regional Landscapes – Rethinking Landscapes, Ecosections and Biogeoclimatic Classification in the face of Climate Disruption*. Unpublished Draft Rpt. Kutenai Nature Investigations Ltd. Nelson, BC. Available at: https://www.kootenayresilience.org/rls

Suggested citation for this document

Carver M and G Utzig 2021. *A Framework for Developing a Scientifically-Defensible Monitoring Network in the Upper Columbia Basin: Steps for Pilot Implementation*. Draft prepared for Living Lakes Canada (March 12, 2021), 10 p.