Regional Geochemical Survey: Delineation of Catchment Basins for Sample Sites in British Columbia

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INTRODUCTION

As part of the regional geochemical survey (RGS) program, stream sediment, lake sediment and water samples have been collected from 59 633 locations since 1976, covering approximately 75% of British Columbia (Lett and Doyle, 2009). Geochemical data from the field and multi-element analyses have been compiled and are available to the public. Jackaman and Balfour (2007) recently reported additional chemical analyses performed on RGS archived samples with funding from Geoscience BC.

The geochemical data of the stream sediment samples often reflects the geology and mineralization in the contributing area. As such, a preferred way to visualize the results is to create thematic maps with colour themes or patterns representing element concentrations in upstream catchment basins (Sibbick, 1994).

Catchment basins are recognized as more effective in defining zones of influence for the geochemical results from stream sediment samples (Bonham-Carter and Goodfellow, 1986; Bonham-Carter et al., 1987). Previous studies have linked the catchment basin, stream order and stream gradient to the source of the anomalies detected in stream sediment, especially in small catchment basins with first- and second-order streams (Hawkes, 1976; Sleath and Fletcher, 1982). This link, however, might be weak or even decoupled when the catchment basins are large, the geomorphology is diverse and the hydraulic forces vary significantly across the catchment area (Leggo, 1977; Ryder and Fletcher, 1991; Fletcher, 1997). Bedrock geology, slope, aspect, vegetation, differential weathering of bedrock, rainfall, wildlife and other physical variations in the catchment basins influence the composition of the stream sediment sample and contribute to within-basin variation (Jackaman and Matysek, 1995; Matysek and Jackaman, 1995; Matysek and Jackaman, 1996).

In BC, preliminary catchment basins were delineated for 290 RGS samples (Sibbick, 1994) covering part of northern Vancouver Island (NTS 092L/03, 04, 05 and 06). These were based on 1:100 000 scale topographic maps that were photo reduced from the 1:50 000 scale NTS maps. Catchment basins were defined as the topographic heights of land that separate stream drainages. Catchment basins were delineated by hand tracing the heights of land (represented by contours) onto a Mylar overlay. The resulting polygons were then digitized at 1:100 000 scale and each polygon labelled to correspond to its RGS sample number. Following a similar method, 3 906 catchment basins were delineated for RGS samples located in 1:250 000 scale NTS map areas 103I, 103J, 103O and 103P (Jackaman and Matysek, 1995; Matysek and Jackaman, 1995; Matysek and Jackaman, 1996).

The previous work demonstrated a new way of disseminating geochemical survey results for stream sediment and water samples. There are, however, shortfalls in the catchment basin methodology and outcome due to the limitation and availability of hydrographic data and spatial technology, including that

- there is no province-wide coverage of catchment basins for the RGS sample sites; only less than 8% of the RGS sites have been delineated and published since 1994;
- the previous delineation process was labour intensive and very time consuming;
- manual catchment-basin delineation has the potential to introduce inconsistency in the results;
- heights of land were not available for every drainage within a catchment basin, impossible to query a given catchment basin at a finer granularity; and
- the 1:100 000 scale topographic base used for the delineation was generated from 1:50 000 scale topographic maps and lacks resolution and detail.

The main focus of the project described in this paper is to develop a fully automated process to yield highly reliable catchment basins for a number of reasons:

- A repeatable algorithm generates consistent catchment basins.
- Delineating catchment basins is possible after corrections or adjustments are made to the sample locations, when new sample sites are available or when new and more detailed topographic maps are available.
- Refining catchment basins with criteria provided by users is possible.
- A processing environment based on open standards or solutions implemented with open standards (such as those by Open Geospatial Consortium and the International Organization for Standardization) ensures its interoperability with lasting relevance in the foreseeable future.
- Rapid processing of province-wide sample sites is possible, and processing of a small group of sites and returning results in real time over a web service is achievable.

This publication is also available, free of charge, as colour digital files in Adobe Acrobat® PDF format from the BC Ministry of Energy, Mines and Petroleum Resources website at http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/Fieldwork/Pages/default.aspx.

The most current and detailed BC Provincial Terrain Resource Information Management (TRIM) watersheds with fully connected stream networks are used as the topographic base in the delineation of catchment basins for stream sediment and water sample sites.

DESCRIPTIONS OF INPUT DATA

Regional Geochemical Survey Data

The RGS data include 59 633 sample locations, field observations and analytical results for up to 40 metals for water, stream and lake sediment samples collected over a period of 30 years. Sample sites are plotted on 1:50 000 scale NTS maps and co-ordinates are estimated or measured. The 1:50 000 scale NTS maps are based on the NAD27 datum and have not been updated since publication.

Of the RGS sample locations, 51 639 are stream sediment and water sample sites. Stream sediment and water samples are collected mostly above the confluences for first- or second-order drainages.

Watersheds and Stream Network Data

Watersheds and stream networks are the topographic drainage base that is used for the delineation of RGS catchment basins. For this delineation exercise, we used a version of the watersheds and stream networks produced in June 2008 by the BC Integrated Land Management Bureau (ILMB). In total, there are 3 241 667 watershed polygons and 4 910 953 stream network edges. The data are derived from the 1:20 000 scale TRIM topographic base and are considered as one of the provincial standard hydrographic datasets with fully connected stream networks and well-formed watershed polygons. Stream data collected through TRIM II and updates from the TRIM data exchange program were not included in the stream networks.

Stream networks have full connectivity by adding 'skeleton' network edges or connectors through water bodies such as lakes, rivers and canals digitized as polygons, in addition to the TRIM hydrographic features, including construction lines for polygon closures or connections.

The watersheds were delineated as polygonal units from height-of-land boundaries generated from the TRIM digital elevation model (DEM) and TRIM hydrographic data. The watershed units are fine-grained; however, they are not subdivided as left drainage and right drainage to a stream network edge. The notion of 0-order drainages is problematic for upstream queries if sample sites are located in those watersheds.

Nongeometric attributes for both watersheds and stream networks include names for hydrographic features, drainage order and magnitude, cross referencing of hydrographic features between data based on 1:20 000 scale TRIM and NTS 1:50 000 scale maps, and hierarchical keys. Modified Strahler drainage order and magnitude (Strahler, 1952) were generated, including the notion of 0-order drainage for small watershed units along river banks or lakes that do not have drainage edges. The notion of hierarchical keys was introduced to provide the ability to carry out upstream and downstream queries in a nonspatial manner. The hierarchical keys were computed as the proportional distance along a stream where a child stream flows into its parent. The hierarchical keys are available in both the watersheds and stream networks.

METHODS

Computing Environment

All the data processing and analyses were carried out in a 32-bit development environment configured for a number of object-relational databases with spatial extension, including PostgreSQL/PostGIS and Microsoft® SQL Server® 2008. Extraction, transformation and loading (ETL) tools include FME from Safe Software, JTS and JEQL (Davis, 2008a, b). The main visualization environment and earlier prototyping were carried out using Manifold® System version 8. Results are stored in a database and were converted by JEQL to KML format for visualization using Google™ Earth.

Additional testing of upstream queries was carried out in a 64-bit environment configured with AllegroGraph RDF Triple Store (Franz, 2008), with stream edges as RDF (Resource Description Framework) triples.

The main programming interfaces are VBscript® in Manifold, SQL for Microsoft SQL Server and PostGIS, PL/pgSQL in PostGIS, Java in AllegroGraph and Perl for batch processing.

A high-level view of the system architecture for this processing environment is depicted in Figure 1. Each of the components consists of a subsystem.

This environment is configured with spatial databases and software components that have either implemented the Open Geospatial Consortium (OGC) Simple Features Specification for SQL (SFS; Open Geospatial Consortium, 1999) or are interoperable at a more primitive and practical level. A major effort was made to ensure the simplicity and consistency in the data model across different subsystems. This practice saves time as data are readily transferable between different subsystems to the environment where performance is optimal. Compliance with OGC SFS has the benefit of implementing the same sets of binary predicates and spatial functions, resulting in the development of applications usable in different subsystems either directly or with minimum modification.

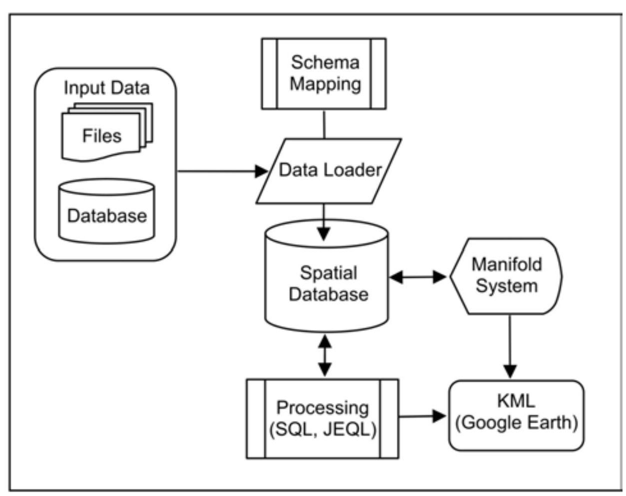

Figure 1. High-level view of system architecture for the upstream processing environment.

The streamlined processes are outlined in Figure 2, with more detailed descriptions in the following three sections.

Data Loading

Before the data are loaded into the spatial database, effort is invested into simplifying data models for the input datasets. The practicality and consistency of data models across different subsystems ensure the interoperability of applications and data in a more meaningful way. Results are achieved through a level of data modelling and automated schema mapping.

Data loading is carried out in batch mode through FME, Manifold and, in earlier tests, through Shape2SQL by SharpGIS (Nielsen, 2008).

When data are loaded into a spatial database, a process is used to validate the geometries against the OGC Simple Features Specifications. The syntax for Microsoft SQL Server is of the form:

```
UPDATE [topobase].[dbo].[wateshed s_poly]
SET GEOM=GEOM.MakeValid();
```

This process automatically converts invalid geometries into valid OGC SFS-type geometries. This step is crucial as the spatial operation using the data can fail if the geometries are not compliant to the OGC standard.

A spatial index is created for every table with geometry. Additional indices are created depending on the query.

For RGS sample sites, a query is used to create a new table with stream sediment and water sample sites only.

Upstream Query

The upstream query is the process used to search and collect all the upstream watersheds. It consists of the following stages:

The first stage is to find watershed polygons that contain RGS stream sediment and water sample sites. These polygons are called 'root' watersheds (Figure 3). A SQL statement to do this would look like:

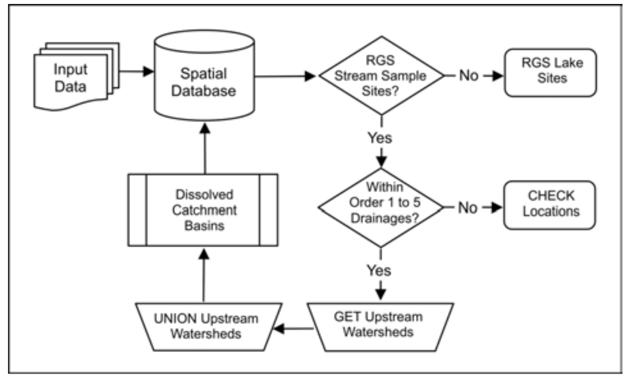

Figure 2. Simplified processing flow diagram.

```
SELECT b.master_id, a.watershed_id INTO
rgs_stream_rootwatershed

FROM watershed_poly a,
rgs_stream_sites_sp b

WHERE ST_CONTAINS(a.geom, b.geom);
```

The catchment basins could include a small downstream area below the sample sites by using 'root' watersheds. If the sample sites are close to the confluences, the downstream areas should be small and insignificant. A refinement on this methodology could eliminate all the downstream areas.

In the second stage, root watersheds, or the equivalent of root stream edges, are used to query and collect the upstream watershed polygons or stream edges. Three methods were proposed. In the first method, the hierarchical keys were used to search the upstream watersheds or stream edges in a nonspatial query. As discussed in the next section of this paper, this is a time-consuming query if the dataset is large.

In the second method, a graph theory (e.g., Bondy and Murty, 1976) approach was used. The basic concept is to use stream networks as edges to form RDF triples as specified by Resource Description Framework (W3C, 2000, 2004), such as:

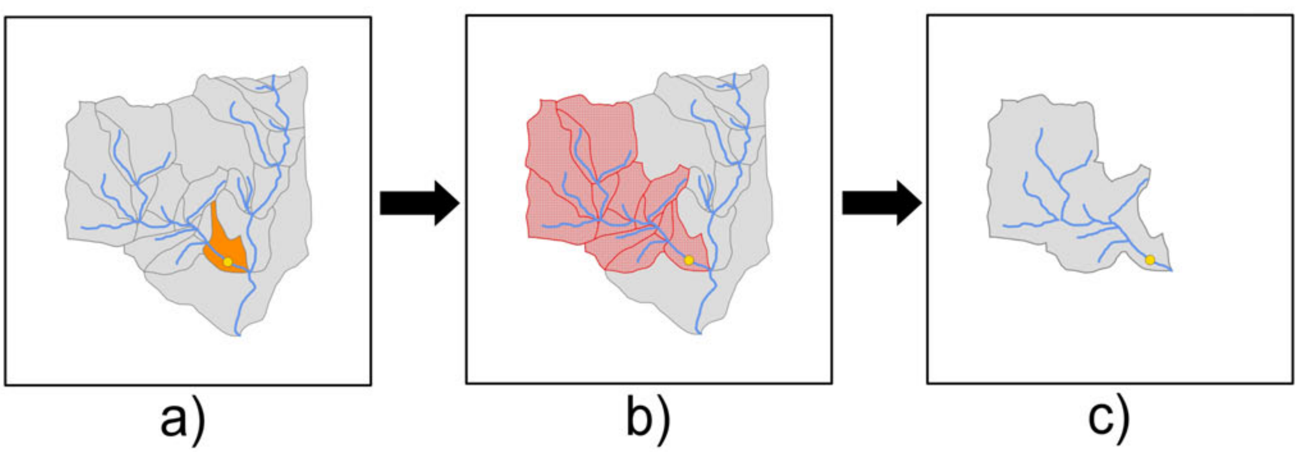

Figure 3. Catchment basin delineation stages depicted with examples: **a)** locate root watershed (highlighted in orange) for a sample site (yellow dot), **b)** retrieve all upstream watersheds (highlighted in red) and **c)** dissolve the upstream watersheds as the catchment basin for the sample site.

```
edge_a, "is upstream of", edge_b
```

Endpoints of stream networks are extracted out of the PostGIS database and are used to extract stream edges and identify their topological relationship through a spatial query such as:

```
SELECT rt.cwb_edgeid, up.cwb_edgeid AS
upedgeid, (rt.the_geom) AS the_geom

INTO bc_upedges_2_sp

FROM all_edge_endpoints rt,
all_edge_startpoints up

WHERE (ST_intersects(up.the_geom,
rt.the_geom)) AND (rt.cwb_edgeid
up.cwb_edgeid);
```

The stream edge triples are loaded into an RDF Triple Store in AllegroGraph, a database and application framework developed by Franz (2008). Upstream query is performed on the stream edge triples through query APIs (application programming interfaces) such as SPARQL (the proposed W3C query language) and Prolog with custom code in Common Lisp. A visual representation of the stream graph edges is shown in Figure 4.

A third method is recursive queries using a common table expression (CTE). It uses the same stream edge triples as the input data loaded into a relational database.

Dissolving Upstream Watersheds

In the last step of the process, the upstream watershed polygons are dissolved for each of the RGS stream sediment and water sample sites.

Dissolving polygons remains one of the most challenging tasks in improving performance. Open standards-based solutions usually implement one of the OGC predicates called 'UNION' to combine or dissolve polygons. The spatial databases tested in our study take considerable time to dissolve a relatively small number of polygons. For the data size in this study, it is not practical to run such a query. Alternative methods within spatial databases were tested, such as the UnionAggregate functions in Microsoft SQL Server along with the PostGIS Analysis Tool (Martinez-Llario et al., 2008) but none provided a significant performance improvement.

A more practical approach is to use JEQL, with the idea of a Cascaded Union function, to dissolve the polygons outside the spatial database in batch mode (Davis, 2008a, b). The JEQL interface uses JTS as the spatial processing engine and can interface with Microsoft SQL Server and PostGIS.

DISCUSSION OF RESULTS

Data Loading Performance

Initially, data loading takes approximately 70 minutes for 4.9 million stream edges and less than two hours for 3.2 million watershed polygons, using a single process from a desktop workstation. Spatial indexing takes approximately a quarter of the load time. Load time can be improved by launching multiple data-loading processes from different workstations.

Locations of RGS Stream Sample Sites

The query to locate root watersheds for the RGS stream sediment and water sample sites reveals that 94% are located within watersheds with drainage orders from 1 to 5, and a small portion are located in watersheds with drainage orders from 6 to 10 (Table 1, Figure 5). There are 228 sites located in drainage order 0 watersheds and another 36 sites that are not contained in any watershed.

The RGS samples sites located in root watersheds with drainage orders from 1 to 5 are used for the next steps in upstream queries.

The RGS sample sites within drainage order 0 or not within any watersheds are separated into another table to verify their locations.

There are cases where the RGS stream sample sites fall in watersheds with drainage order 0 and the watersheds appear to be skinny in shape and not adequately subdivided along river and lake banks (Figure 6). Upstream queries on such a root watershed could return a very large catchment basin (e.g., over half a million upstream watersheds).

The sample sites not within any watersheds are all located offshore, but within a short distance of the sea coastline, which is likely due to resolution differences between the 1:50 000 scale maps and 1:20 000 scale maps. These sample sites will be identified in a separate study with streams in the original 1:50 000 scale NTS maps in digital copy. With an existing cross-referencing between the 1:50 000 scale hydrographic features and the more detailed 1:20 000 scale TRIM streams, the RGS sample streams will be matched or linked to TRIM streams and the RGS sample sites transferred or snapped to the TRIM streams.

The RGS sample sites within watersheds with a drainage order above 5 could include large upstream areas that are meaningless when the entire catchment basin is delin-

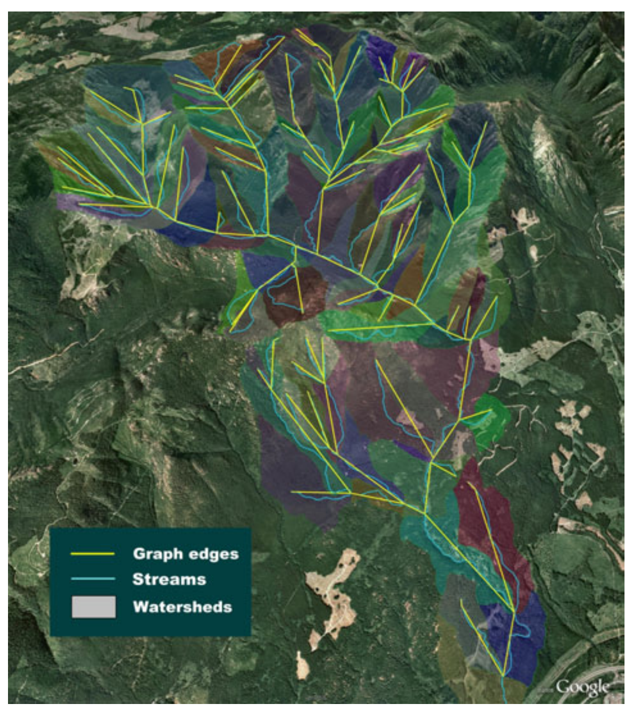

Figure 4. Visual representation of upstream graph shown on Google Earth (Google, 2008).

Table 1. Summary of RGS stream sediment and water sample sites and drainage orders (note: 36 sites are not contained in any watershed).

Stream Order	Number of RGS Sites	Percentage
0	228	0.44%
1	6544	12.68%
2	11736	22.74%
3	16034	31.07%
4	10148	19.67%
5	4291	8.32%
6	1550	3.00%
7	610	1.18%
8	233	0.45%
9	191	0.37%
10	38	0.07%

eated. In this study, these sample sites (less than 5% of the total) were filtered out for dissolving watershed polygons.

Upstream Watersheds

The query on searching and collecting upstream watersheds for the RGS stream sediment and water sample sites was carried out in PostGIS and tested in Microsoft SQL Server. The query initially returned greater than 47 million polygons in 20 hours, averaging one million upstream watershed polygons in 2.3 hours. The sample sites within drainage order 0 or above 5 forms only 5% of the RGS stream sample sites, but 87% of the upstream watersheds are associated with them. The highest RGS site has over 500 000 upstream watersheds. These sample sites are filtered out for further processing because the sites need to be validated and an overly large catchment basin is perhaps not useful. This study processed the remaining 5.8 million upstream watersheds for 51 639 stream sediment and water

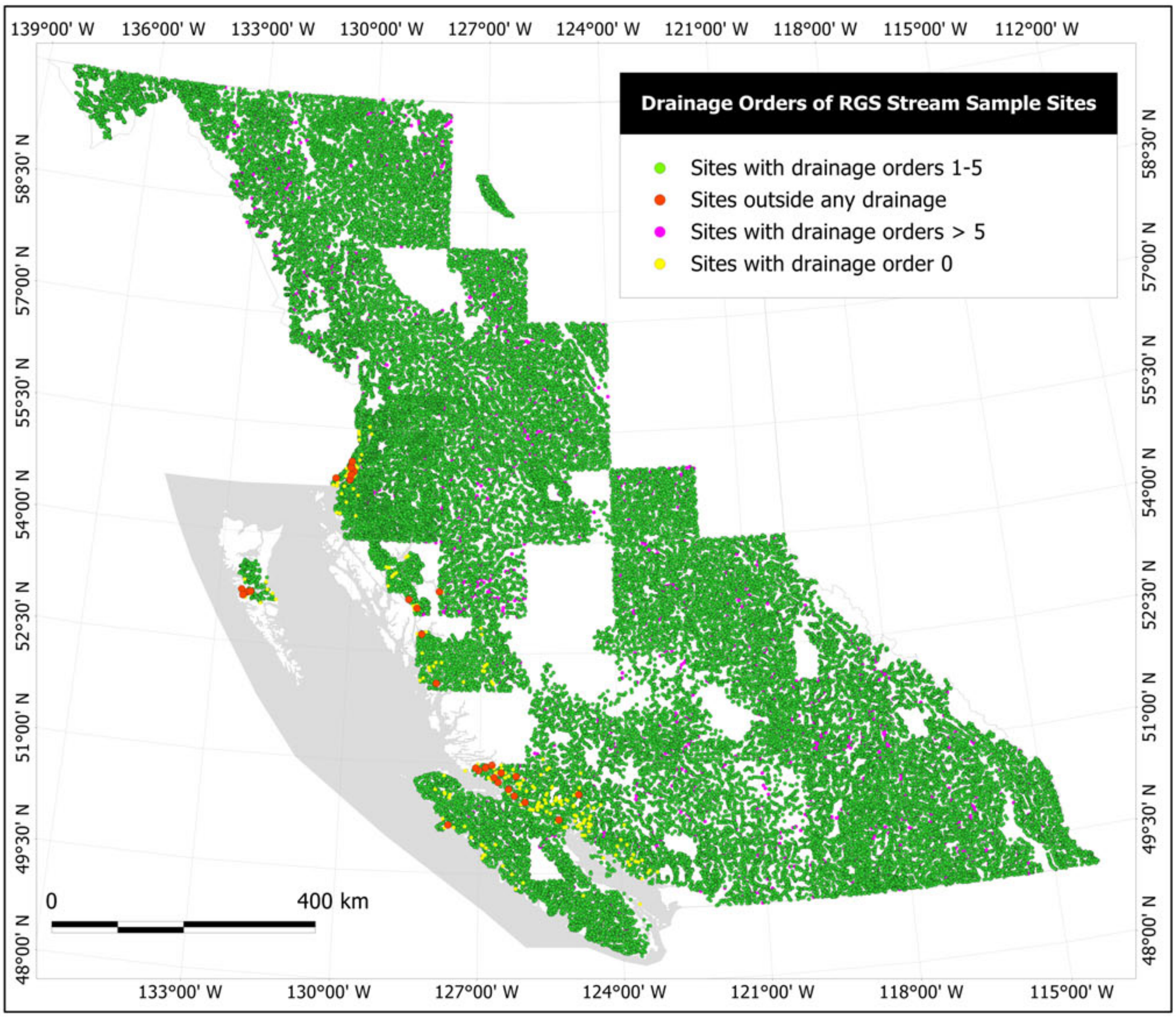

Figure 5. Drainage orders of RGS stream sites.

sample sites that fall mostly within watersheds with drainage order from 1 to 5.

In a separate test, the AllegroGraph RDFStore™ was used to traverse the edge trees and retrieve 1 000 000 upstream edges in only 6 seconds (not including the time to write results). Traversal of edge trees happens at basically computer memory speed. While it is recognized that this is not a fair comparison, the performance numbers nevertheless are interesting enough to warrant further investigation of graph-theory–based technology such as AllegroGraph for the improvement of upstream queries, in addition to its emerging spatial-temporal reasoning capabilities in applications such as building knowledge base with RDF triples (Aasman, 2008a, b) and mapping mineral potential.

The performance from recursive CTE is also impressive. They are capable of retrieving over 1 000 000 upstream edges in less than 50 seconds in a relational database, including the time to group and write output.

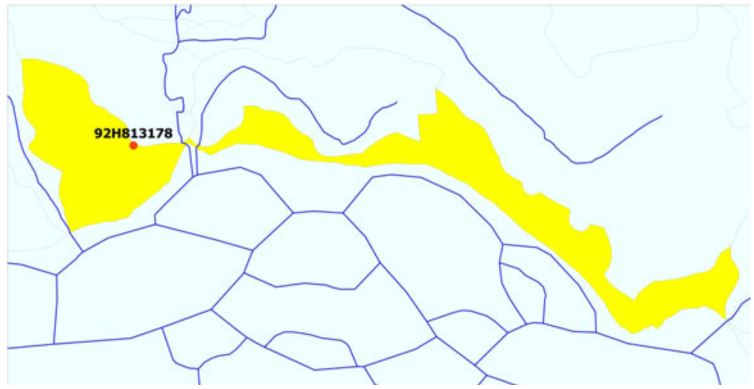

Figure 6. Example of an RGS stream sample located in a 0-order watershed adjacent to a river. Note the skinny shape of the watershed is highlighted.

Results on Delineating Catchment Basins

In total, 5.7 million polygons were successfully dissolved into 51 639 catchment basins in 3 hours by JEQL interfacing into PostGIS, in a batch mode with RGS sample sites divided into groups of 1 000 sample sites. Since the

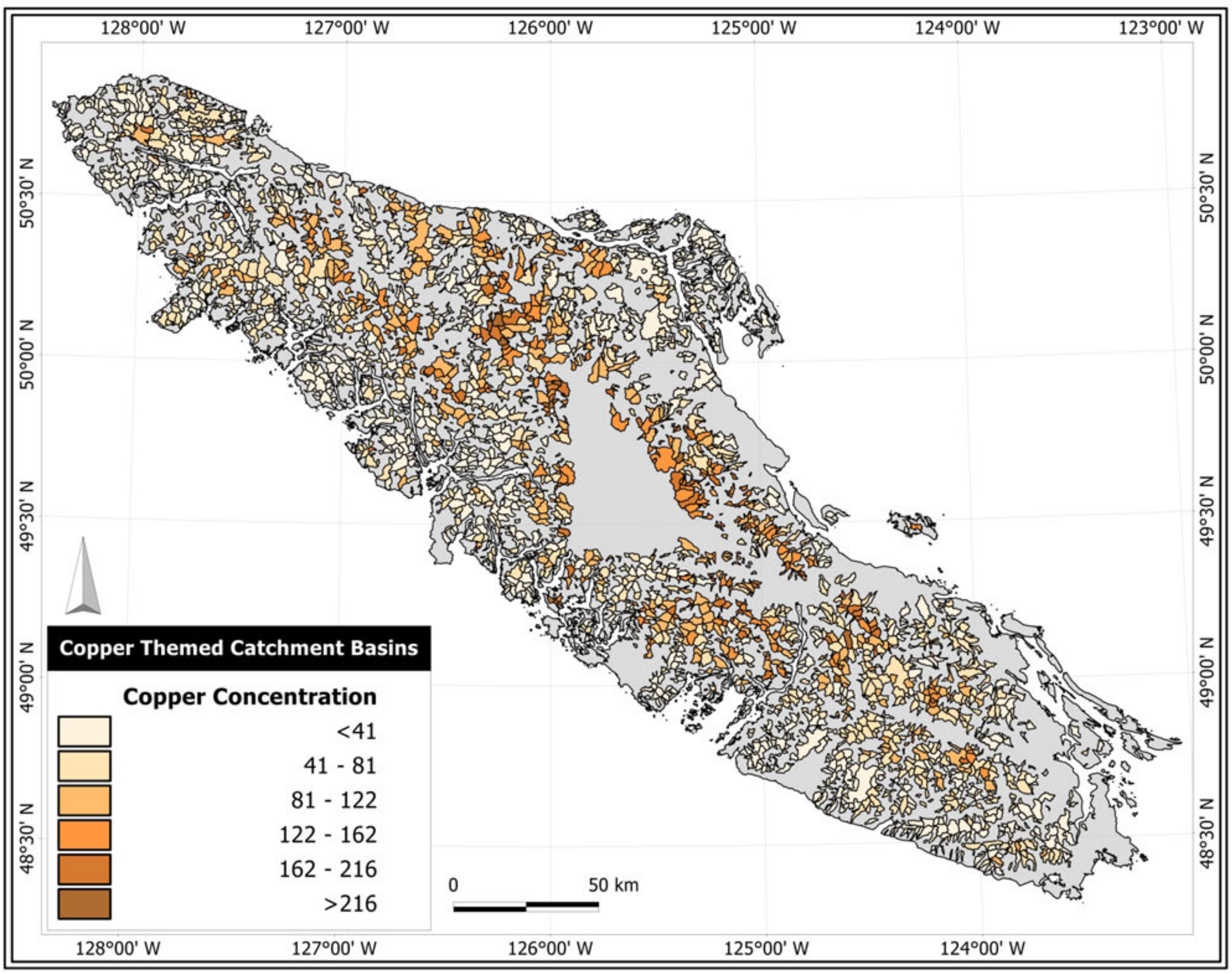

Figure 7. Example of catchment basins themed with copper concentrations for RGS sediment samples on Vancouver Island.

processing is carried out on desktop workstations outside the database, multiple processes could be launched simultaneously from different desktop workstations to significantly improve performance, which is being further tested.

In an earlier development, polygons were dissolved with VBscript in Manifold with results shown in Figure 7. In small batch testing, both PostGIS and Microsoft SQL Server were capable of dissolving up to 30 000 polygons within 30 minutes. When all 5.7 million polygons were submitted for dissolving, the query ran for up to six days without returning any results.

Known Issues

The catchment basins were delineated for RGS stream sediment and water sample sites that were considered to be reasonably correct. Fewer than 5% of the sites were not processed due to their locations either outside any watershed or within watersheds with a drainage order 0 or above 5. If these errors are eliminated, it should take less than two days to reprocess all the RGS stream sediment and water sample data.

Even after filtering out the RGS sample sites within watersheds with drainage order 0 or above 5, some sample sites still have relatively large catchment basin areas. A new version of catchment basins should be delineated with limited upstream reaches, such as within an arbitrary cut-off distance.

Watersheds with drainage order 0 are still an issue. A legitimate sample site located within this type of watershed will invalidate upstream query results.

The hydrographic base does not have the notion of left and right drainages for a given stream edge, limiting the possibility of further refinement of catchment basins with finer granularity using criteria such as slope or geology to compare results on the left drainage versus the right drainage.

CONCLUSIONS

A fully automated process was developed for the delineation of catchment basins (also known as an upstream query). It was applied for the delineation of catchment basins for the RGS stream sediment and water sample sites. The results will be released once data quality has been verified and aberrant locations for a small number of sample sites are addressed.

Object-relational databases with spatial extension have reasonable performance in data storage and simple queries, but are not fast enough for intense processing or complex spatial or nonspatial queries. Java application-based solutions outperform spatial databases by a wide margin in intense processing. Graph-theory–based methods also potentially open the door for other applications in geoscience.

This processing is facilitated in an interoperable system environment configured with spatial databases and Java applications that are implemented with open standards-based geometry data type, binary predicate and spatial functions.

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