# INTEGRATED GROUNDWATER RESOURCE ASSESSMENT OF FRACTURED BEDROCK AQUIFERS IN THE GULF ISLANDS, BC

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Abstract: The Gulf Islands are a network of small rural island communities located in the Georgia Basin region of Southwestern British Columbia. They are representative of many communities across Canada that depend primarily on groundwater for domestic and agricultural use. Situated in the active forearc of the Cascadia subduction/accretion complex, the structurally–controlled fractured bedrock aquifers in this region are highly partitioned, difficult to map in detail, and vulnerable to both overuse and contamination. Increased water demand from population growth and development have already contributed to salt water intrusion, increased numbers of abandoned wells and significant declines in water quality during the summer months. Working in collaboration with groundwater professionals in the public, private and academic sectors, we have developed a suite of models to derive an assessment of aquifer vulnerability and sustainable yield in the Gulf Island region. Our intent is to help decision makers better understand the complex hydrogeology of the region and to incorporate this understanding into a planning and policy development context across both local and regional jurisdictional levels of government. Collectively, these resource assessment models provide a means of evaluating the impacts of current land use strategies on available water resources in the Gulf Islands, and a framework for exploring alternate strategies for resource management.

Résumé: Les îles du Golfe sont un réseau de petites communautés rurales situées dans la région du bassin de Georgia en Colombie-Britannique. Elles représentent plusieures communautés à travers le Canada qui dépendent principalement sur les eaux souterraines pour les utilisations domestique et agricole. Situés dans le bassin d'avant-arc actif de la zone de subduction et d'accrétion Cascadia, les aquifères contrôlés par les éléments structuraux de la roche en place sont fortement fracturés, difficiles à tracer en détail et vulnérables à la surconsommation et à la contamination. Une demande accrue en eau en raison de la croissance de population et du développement a déjà contribué à l'intrusion d'eau salée, à l'abandon d'un grand nombre de puits et à la déterioriation importante de la qualité de l'eau pendant l'été. En collaboration avec des spécialistes en eau souterraine des secteurs publics, privés et scolaires, nous avons développé une suite de modèles pour dériver une évaluation de la vulnérabilité des aquifères et le rendement durable dans la région des îles du Golfe. Notre propos est d'aider aux décideurs à comprendre l'hydrogéologie de la région et d'incorporer cette notion dans un contexte de politiques de développement et d'aménagement pour toutes les juridictions locales et régionales du gouvernement. Ensemble, ces modèles d'évaluation de ressource fournissent des moyens d'évaluer les impacts des stratégies courantes d'aménagement et d'urbanisme sur les ressources d'eaux souterraines disponibles dans les îles du Golfe. De plus, les modèles,peuvent développer un cadre pour explorer de nouvelles stratégies de gestion de la ressource.

## 1. Context and Focus

The Georgia Basin (Figure 1) is home to the urban centers of Vancouver and Victoria, and one of the most densely populated and fastest growing bioregions in Canada. With a population growth rate of thirty-five percent, it is anticipated that the region will swell to approximately four million people by the year 2020 (Georgia Basin-Puget Sound Ecosystem indicators Report, 2002). Over this same period of time, it is estimated that regional impacts of global climate change will likely reduce surface water supplies and rates of recharge, thereby placing increasing demands on available groundwater resources. These trends underscore the need for tighter coupling between ongoing scientific research, land use planning and water management strategies if we are to collectively maintain and protect renewable groundwater resources that will be required to balance competing economic, environmental and human needs in the region.

This paper highlights Phase I results of an ongoing collaborative project aimed at bridging the gap between groundwater science, policy development and community planning in the southern Gulf Island region of the Georgia Basin. We describe methodologies for assessing intrinsic vulnerability and sustainable yield in fractured bedrock aquifers and explore strategies for situating the outputs of these assessments more directly in a planning and policy development context. The initial phase of this project (Phase I) was undertaken as part of the aquifer characterization and mapping component of the Geological Survey of Canada Groundwater (GSC) Program. The project brings together expertise in the fields of groundwater hydrogeology, bedrock geology, structural geology and tectonics, GIS and modeling, education and community outreach, and represents an interactive


**Figure 1**: The Georgia Basin, British Columbia
(Transboundary Georgia Basin-Pudget Sound
Environmental Ecosystem Indicators Working Group, 2002)

partnership between academia, Federal and Provincial science agencies, regional planners and member communities in the Gulf Island region.

## 2. Background

The Gulf Islands (Figure 2) comprise an archipelago of thirteen island communities situated in the rural heartland of the Georgia Basin, between the Greater Vancouver Regional District (GVRD), the Capital Regional District (CRD) of Victoria and rapidly growing communities in the adjacent Cowichan Valley, Nanaimo and Sunshine Coast regional districts. The islands are topographically subdued (100-350m) with limited surface water supplies, and are characterized by glaciated ridges and valleys that mirror the geometries of underlying bedrock formations. Structurally controlled bedrock aquifers and, to a lesser extent, unconfined shallow (<18m) granular aquifers are the principle groundwater resources in the region, supplying more than eighty percent of the existing needs for domestic and agricultural use.

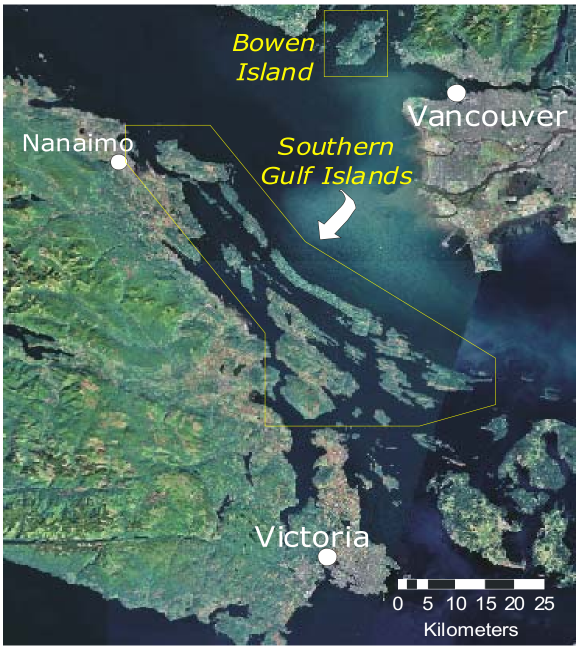


**Figure 2**: The Gulf Islands

Although prospective, most of the deeper and more reliable bedrock groundwater systems are structurally complex, poorly understood from a hydrogeological perspective, and beyond the scope of existing aquifer assessment and mapping methodologies (Aller et al., 1987; Ronneseth et al., 1995). Overuse of these fractured bedrock aquifers in several Gulf Island communities has already contributed to instances of saltwater intrusion, an increasing number of abandoned wells and measurable declines in water quality in the summer months. The susceptibility of these aquifers to overuse and contamination can be expected to increase as population densities, development infrastructures and the demand for reliable community water resources continue to grow in the region.

### 2.1 Policy Framework

Provincial legislation in 1975 established the Islands Trust as a federation of local island governments with regional planning authority and a mandate to "preserve and protect the trust area and its unique amenities and environment for the benefit of the residents of the trust area and of British Columbia generally, in cooperation with municipalities, regional districts, improvement districts, other persons and organizations and the government of British Columbia" (Islands Trust, 2003). By 1987, the Islands Trust Act was amended to include local community planning authority, comparable to that of a regional district operating under guidelines of the Municipal Act. In 1993, the Trust Policy Statement bylaw was enacted as a planning framework to help guide decisions on growth management and land-use issues for the region and within individual island communities. The bylaw encompasses a number of policy guidelines that specifically address groundwater resource management in the Trust area, including conservation of wetlands and recharge areas, alternate strategies for demand-side management and support for local stewardship activities.

It is the cumulative impact of individual and collective decisions made at the community and regional district level that have the most significant impact on the protection and management of groundwater resources. And, it is at this level of policy development and decision-making where the outputs of academic, private sector and federal-provincial groundwater studies (information knowledge and expertise) are most relevant, yet often least accessible.

## 3. Bridging the Science-Policy Gap

Like many rural communities across Canada, the Gulf Islands have built up a wealth of local knowledge and expertise over the years to address issues relating to groundwater resource management, including strategies for mitigating effects of surface contamination and over consumption. Much of this knowledge resides with local planners, water purveyors and community stewardship groups acting on behalf of their constituents. It is, however, not always well-integrated with ongoing groundwater research in academic and/or public science sectors, and is often not accessible to those making decisions at other jurisdictional levels of government.

In an effort to bridge these gaps in understanding and to broaden the network of collaboration, the Gulf Island Groundwater Initiative undertook the design and facilitation of a series of consultation workshops through interactive partnerships with the Islands Trust and member communities of the Trust area. The intent of the workshop process was to share information and knowledge on key water resource issues in the region, and to co-develop an educational poster (Waterscapes) and accompanying outreach materials to help promote understanding and wise use of freshwater resources by island residents and visitors to the Gulf Islands. The community engagement process was coordinated through a steering committee which included elected officials, planners, groundwater professionals, educators and volunteer stewardship coordinators.

Collectively, the working group identified eight key water issues for the region; 1) water conservation, 2) seasonal precipitation, 3) freshwater storage, 4) water for ecosystem use, 5) hydrogeology of fractured bedrock aquifers, 6) aquifer vulnerability, 7) water scarcity and 8) land use strategies. Following this initial phase of issue identification, the working group then determined key messages for each of the major topics and worked with GSC staff to design and develop a suite of scientific illustrations and accompanying storylines to represent and communicate key concepts of groundwater science and resource management in the region. Results of this work led to the joint publication of a 'Waterscapes' poster series (Turner et al., 2004) and accompanying on-line resources for use in support of ongoing community outreach and stewardship activities across the Gulf Island region (Figure 3).

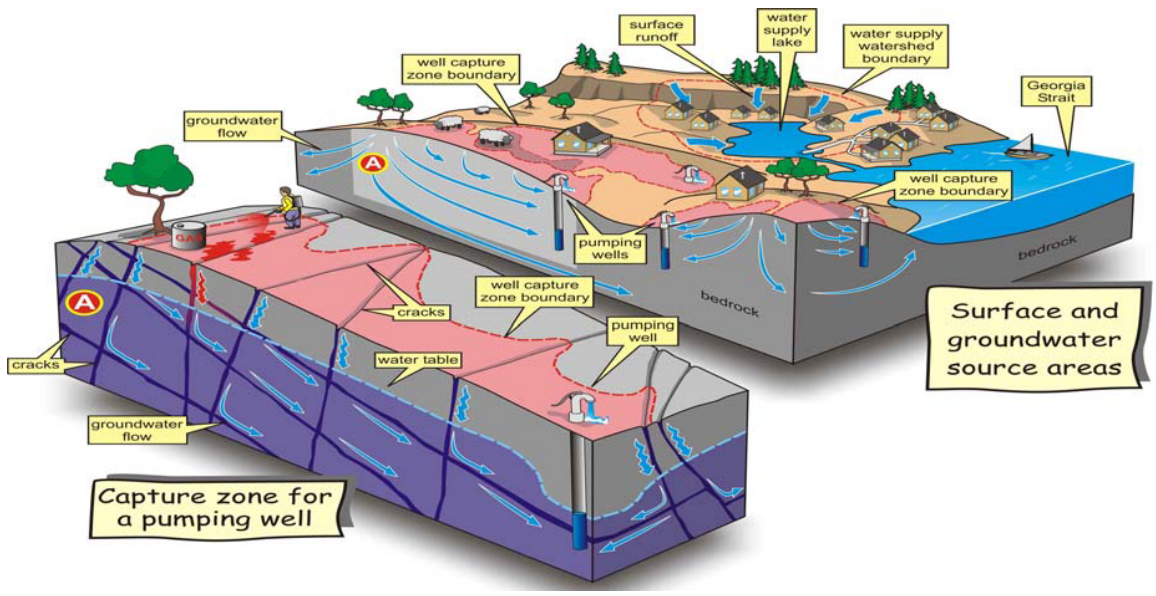


**Figure 3**: Surface/groundwater interactions in the Gulf Islands (Turner et al., 2004)

Through this process of collaborative design and deliberation, the working group also succeeded in evolving a shared understanding of structurally controlled bedrock aquifer systems, and in identifying strategies to help coordinate and promote a science-based approach to groundwater resource management in the Gulf Islands. It is within this context, and with the intent of supporting ongoing regional and community planning activities, that we undertook the next step in the process of developing an integrated modeling framework for assessing the intrinsic vulnerability and sustainable yield of structurally controlled bedrock aquifers in the region.

## 2. Groundwater Resource Assessment

The majority of bedrock aquifers in the Gulf Island region tend to be highly partitioned, difficult to map in detail, and vulnerable to both overuse and contamination. They are hosted primarily in folded and faulted sedimentary rocks of the Nanaimo Group (forearc basin assemblage) or in structurally complex metamorphic and plutonic rocks (accreted island arc assemblages) of an underlying crystalline basement complex, known as Wrangellia. The region is situated in the forearc of the active Cascadia subduction/accretion complex and records a Neogene (21Ma-recent) history of brittle faulting and associated deformation.

The geometry and kinematics of these cross-cutting brittle structures reflect a process of inhomogeneous strain partitioning in the upper crust that is believed to be associated with both margin-normal and margin-parallel shortening along the active plate margin of North America (Journeay and Morrison, 1999). Bedrock aquifers away from major fault and fracture systems are characterized by relatively low hydraulic conductivity and low primary porosity (~0.05%). Previous hydrogeologic studies and drilling reports (e.g., Hodge, 1995; Dakin et al., 1983; Allen et al., 2002) have demonstrated that the majority of prospective bedrock aquifers are channeled along the younger Neogene fault and fracture systems, and are characterized by variable but increased secondary permeability.

Informed by the results of ongoing process-based hydrogeologic modeling in the southern Gulf Islands (Allen, et al., 2002), we have developed a framework for integrated resource assessment that focuses primarily on regional groundwater protection and resource management objectives (characterizing aquifer vulnerability and sustainable yield) and, to a lesser extent, on the process of groundwater flow within individual bedrock aquifers. The framework is based on a conceptual model that describes the overall hydrogeogic setting of structurally controlled groundwater flow systems in the Gulf Islands (Mackie, 2000; Mackie et al., 2001), and includes both a multi-parameter geospatial index model (Denny et al. (in prep.)) for assessing intrinsic vulnerability of structurally controlled bedrock aquifers, and a stock-flow (STELLA©) water budget model (Forster and Journeay (in prep.)) for evaluating overall sustainable yield of freshwater resources in the Gulf Island region. Outputs of these resource assessment models are combined with socio-economic information in the context of an integrated assessment modeling framework to assist planners and resource managers in evaluating trade-offs associated with alternate land use development and regional growth strategies.

### 2.1 CONCEPTUAL MODEL

The general hydrogeologic model proposed for the Gulf Islands (Mackie et al., 2001, Mackie, 2000) is based on the concept of hydrostructural domains, which are defined on the basis of lithology and structural setting. The model takes into account combinations of fracture density, orientation, aperture and proximity to cross-cutting faults and fracture systems, and defines the hydrogeologic system in terms of five major components (Figure 4); Unit 1: thin (<18m), unconfined granular aquifers, largely situated in valley bottoms, Unit 2a: massive sandstone-dominated units with relatively low background fracture intensity and low permeability, Unit 2b: intercalated mudstone-dominated units characterized by a closely-spaced fracture cleavage foliation and elevated primary permeability, Unit 3a: cross-cutting composite fault zones and Unit 3b: discrete fault-fracture networks marked by brittle fracturing, local brecciation and relatively high secondary permeability.

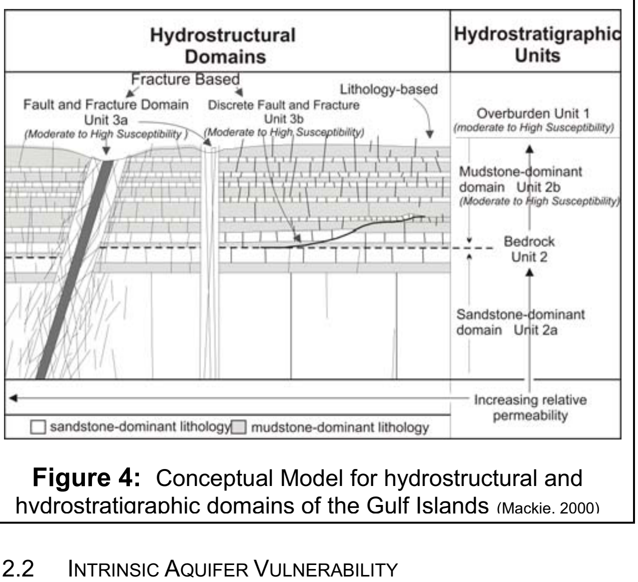


**Figure 4:** Conceptual Model for hydrostructural and hydrostratigraphic domains of the Gulf Islands (Mackie, 2000)

### 2.2 INTRINSIC AQUIFER VULNERABILITY

Although routine practice in unconfined granular aquifers, a full assessment of *aquifer vulnerability* in fractured bedrock systems requires a thorough understanding of structurally controlled fluid-rock interactions over time, process-based modeling of the rates and directions of groundwater flow, and detailed information on the composition, location and intensity of point and non-point sources of contamination. As a result, these studies are usually limited in spatial extent, targeted on specific types and/or sources of contamination, and require ongoing collaboration with groundwater scientists to translate model outputs and associated uncertainties (vulnerability and risk) into a planning and/or policy development context (Focazio et. al., 2002).

*Intrinsic aquifer vulnerability* is a more general form of resource assessment that reflects both the physical characteristics of the groundwater flow system (*intrinsic susceptibility*) and the potential for naturally occurring and/or anthropogenic sources of contamination to enter the aquifer over time. Assessment of intrinsic vulnerability can be undertaken at a regional scale using a combination of geospatial and/or statistical modeling techniques. Outputs of these models provide map-based representations of relative vulnerability (high, medium and low), and are often used as an overarching framework within which to situate more detailed process-based studies of aquifer vulnerability. Although subjective, assessment of intrinsic aquifer vulnerability provides an efficient means of integrating expert and local knowledge of groundwater resources, and is more easily translated into a regional planning and/or policy development context.

#### 4.2.1 METHODOLOGY

In an effort to balance resource management objectives and available information on groundwater flow and potential sources of natural and anthropogenic contamination in the Gulf Islands, we opted for a more general index-based approach that extends the well-known DRASTIC methodology (Aller et al., 1987) of intrinsic vulnerability assessment for use in more complex fractured bedrock aquifers. The standard methodology involves the integration of available information on physical aquifer characteristics, including depth to water table (D), net recharge (R), aquifer media (A), soil media (S), topographic slope (T), impact of vadose zone (I) and hydraulic conductivity of the aquifer (C). Using a raster-based GIS modeling framework (Denny et al. (in prep)), we integrated water well and digital terrain data with information on bedrock geology, soil type and hydraulic conductivity (pump test results) to evaluate the standard DRASTIC parameters for the Gulf Islands. Rates of net groundwater recharge (R) were calculated using the US EPA model HELP (UnSat Suite, Waterloo Hydrogeologic Inc.). The effects of cross-cutting fault and fracture networks and regional tectonic stresses were evaluated by compiling information gathered through remote sensing and field-based structural studies in the Cascadia forearc (Journeay and Morrison, 1999; Mackie, 2000). Physical characteristics of individual fault and fracture systems, including width, length, fracture intensity, connectivity and orientation with respect to regional tectonic stress, were used in deriving an additional parameter (*Fm*) to extend the DRASTIC framework for assessing the effects of secondary permeability on intrinsic vulnerability in fractured media.

### 4.2.1 Results

This modified version of index assessment, known as DRASTIC-Fm (Denny et al. (in prep)), provides a means of characterizing and mapping intrinsic susceptibility and assessing intrinsic vulnerability of fractured aquifers in the Gulf Islands due to a range of potential hazards, including salt water intrusion in coastal areas that are exposed to over pumping, and various types of point and non-point source contamination (Figure 5).

The model is highly sensitive to variations in soil media, depth to water table and proximity to known fault and fracture systems. Regions of low and moderate susceptibility (36-106) occur at higher elevations in areas where depth to the water table is greatest. These are, however, also regions of groundwater recharge and would be more highly vulnerability to surface contamination. Regions of moderate and high susceptibility (106-194) occur along northerly trending fault and fracture systems (Units 3a and 3b), in areas where the water table is within 20 meters of the surface, and in areas underlain by coarse-grained glacial sediments (Unit 1) or fractured mudstone-dominated bedrock units of the Nanaimo Group (Unit 2b). Areas of moderate and high susceptibility that are also within groundwater recharge zones would be most vulnerable to surface contamination. Regions of high susceptibility and that are most vulnerable to saltwater intrusion occur along desirable coastal shorelines where cumulative pumping rates are high, and in places where the shoreline is transected by northerly-trending fault and fracture systems. Overall, there is good correlation between model outputs and water chemistry data that record instances of saltwater intrusion and with measured water yield along identified zones of increased secondary permeability.

DRASTIC-Fm model outputs provide a means of systematically mapping aquifer characteristics and intrinsic vulnerability for fractured bedrock groundwater systems, but do not provide an objective measure of uncertainty. As such, they are intended primarily as a means of establishing a regional framework of groundwater resource assessment in which to situate more detailed process-based studies of groundwater flow and aquifer vulnerability. The hand-off and interpretation of these results to water resource decision makers would require further deliberation to both fine-tune model outputs for specific management objectives (vulnerability to salt water intrusion, recharge protection areas, etc), and to translate the outputs into a set

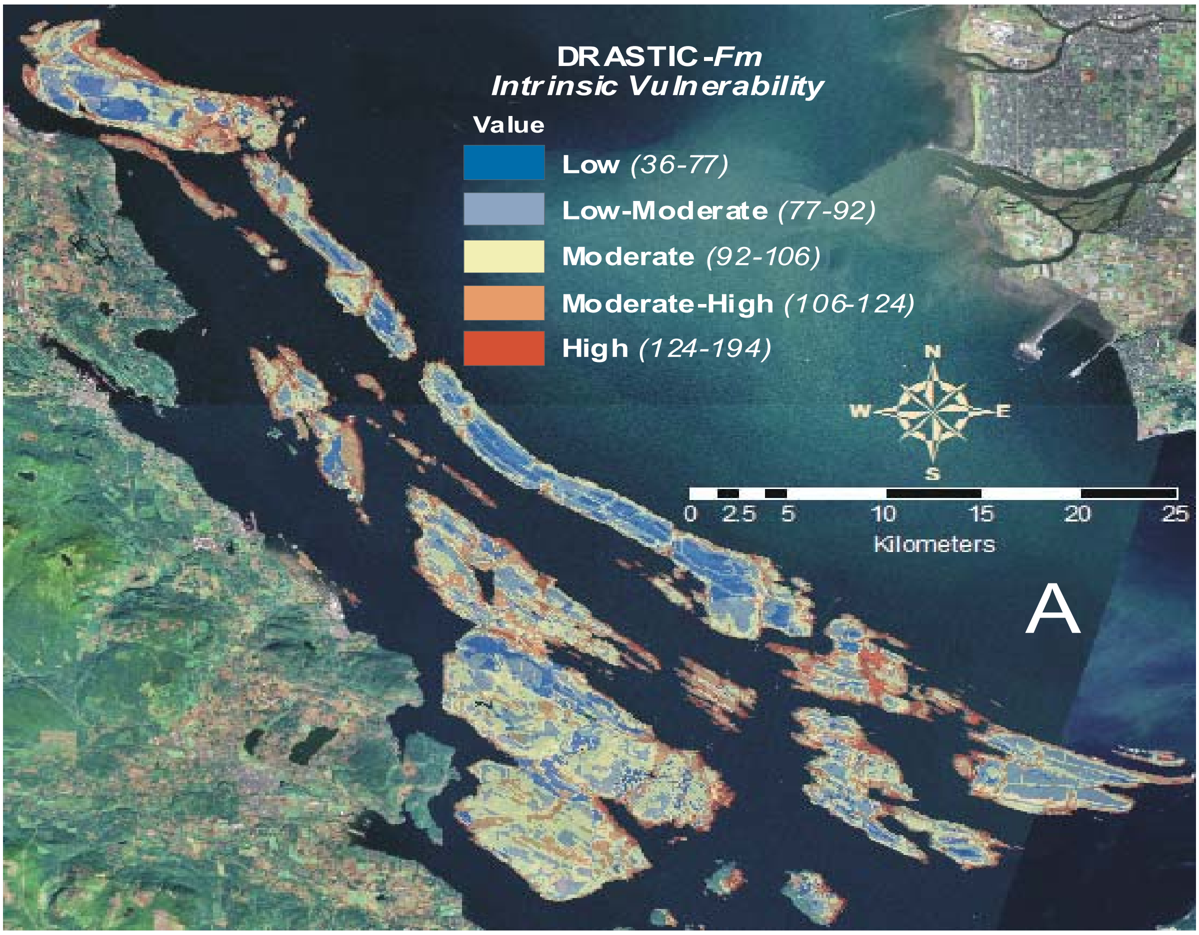


**Figure 5**: Characterization of intrinsic groundwater susceptibility in the Gulf Islands.

of corresponding policy guidelines that could be used in the context of land use and/or strategic planning.

## 3. Sustainable Yield

In addition to being vulnerable to surface contamination and saltwater intrusion, fractured bedrock aquifers of the Gulf Islands are also vulnerable to over-consumption. Many of the islands experience water shortages during summer months, when yearly supplies of surface and groundwater are lowest and cumulative demands from both full-time residents and seasonal visitors are highest. These seasonal fluctuations are exasperated by longer-term trends in climate change, increasing population growth in the region and associated impacts of development infrastructure and changing land use. For the purposes of this study, we interpret sustainable yield to be a state of dynamic equilibrium in which current and projected demands on available freshwater resources do not exceed the capacity of surface and groundwater supplies to balance environmental and human needs over longer-term strategic planning horizons (10-40 years). It is a more general form of a water budget calculation in which rates and fluxes in recharge and groundwater flow can be quantified, usually at the scale of an individual aquifer system.

Assessment of sustainable yield for an island system requires information on current and projected demand (environmental, residential, commercial and industrial), estimates of overall surface and groundwater supply, and potential impacts of climate change. Variables that have the greatest impact on overall yield include rates of population growth, changing patterns of human settlement and water use and overall rates of recharge, which can be influenced by impacts of climate change and land use practices. Given the number of variables and associated uncertainties, we opted for a backcasting approach to evaluating sustainable yield. Backcasting (Robinson, 1982) is an approach to systems modeling that involves working backwards from a particular desired future end-point or set of goals to the present, in order to determine the feasibility of that future and the policy measures that would be required to reach that point. Backcast models deal explicitly with uncertainty by expressing system behaviour in terms of feasibility, choices and consequences, and are designed to focus on management objectives by determining the freedom of action, in a policy sense, with respect to possible futures (Tansey et al., 2004).

### 3.1 Methodology

Working in collaboration with Craig Forster at the University of Utah (Forster and Journeay (in prep.)), we have developed and prototyped a backcast model in STELLA© for assessing sustainable water yield in island systems. The model, illustrated schematically in Figure 6, captures principal aspects of the hydrogeologic setting in the Gulf Islands (Surface Water Supply and Groundwater Supply Sectors) and provides a means of accounting for climate change, population growth (Housing Growth Sector), and changing patterns of settlement and associated water use (Water Use sector). Each node in the model represents a system variable that is expressed numerically as an assumption, or as an algorithm (indicator) that reflects changing properties of the system over time. Nodes are connected by flows (curved lines in Figure 6) that make explicit the interactions between system components, including dependencies, causal relationships and feedback loops. These interactions are expressed through a combination of IF-THEN-ELSE logic rules and methodologies for evaluating system components that vary continuously over time.

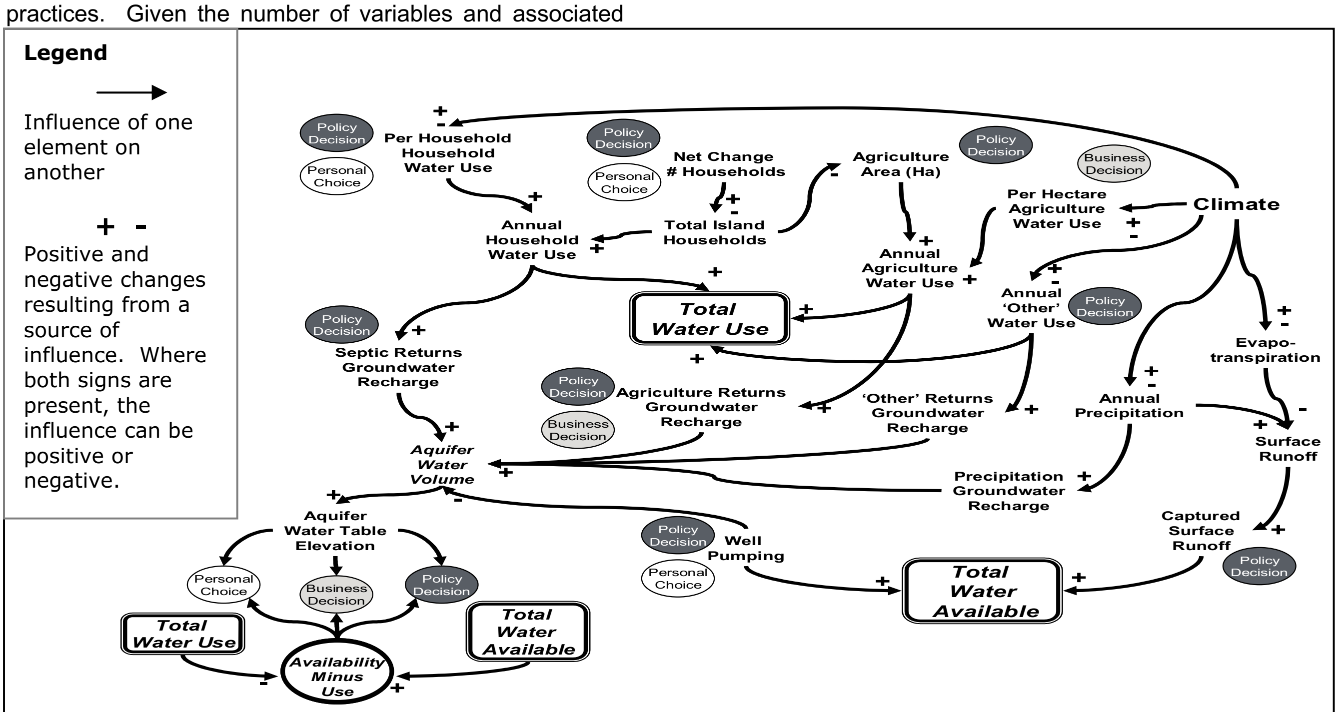


**Figure 6**: Systems flow diagram of the Gulf Islands sustainable yield model. (Forster and Journeay (in prep.))

The STELLA© map also makes explicit those components of the model where human decisions (Personal Choice, Business Decision, Policy Decision) are made that can affect the way the system operates. For example, a combination of personal choice (household size, desire to move to or from the island) and policy decisions (land use regulations and zoning) affect anticipated growth in construction of homes for a growing population. In addition, during periods of low precipitation a farmer may make a business decision to fallow crops or change to low water-use crops. These decisions and choices may be affected, in part, by knowledge that aquifer water levels are declining or by the reality of water shortages (when the available water is insufficient to supply the desired use). At present, only a subset of the possible choices and decisions are explicitly implemented in the model. Options are provided, however, for adjusting input parameters in ways that might reflect specific decisions or choices that might be made in the future.

### 3.2 Results

For purposes of testing the model, we used available datasets for Bowen Island (Figure 2), where detailed information on population growth, sources of water distribution (wells, surface water intakes, service connections, etc.) and rates of water use have been gathered and maintained over the years by water system purveyors and local stewardship groups. If default settings for water demand, water use and water supply are held constant throughout a 50-year simulation period (1980-2030), the results indicate that sustainable yield would be exceeded within the next 25-30 years.

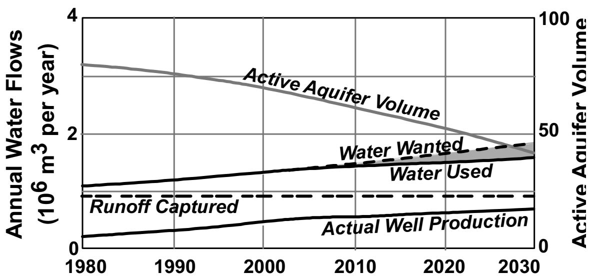


**Figure 7**: Sustainable yield model outputs
(Forster and Journeay (in prep.))

In this scenario, it is assumed that total water used increases with population growth. Because the water made available by capturing surface runoff is held constant, growth in water used is supported only by growth in well production as new wells are drilled. After about 2005, however, the addition of new wells fails to supply the additional water needs and the gap between water wanted and water used (grey zone in Figure 7) grows over time. Continued growth in well production leads to rapid decline in the active aquifer volume (grey solid line in Figure 7) and concern that the groundwater resource may be damaged by overexploitation.

The point of sustainable yield in this scenario, that is the time at which the community would begin to mine available freshwater reserves, occurs between 2030 and 2035. Based on density allocations in the existing land use bylaw for Bowen Island and current trends in population growth, this is also the time at which it is anticipated the community would reach build-out. Policy options that might be implemented to mitigate long-term drought include: water conservation, changes in agricultural practices, increasing surface runoff capture capacity, augmenting water supplies with desalination of sea water, and restrictions on groundwater pumping rates.

What-if scenarios generated by adjusting variables and assumptions in the model provide a means of visualizing and understanding complex system dynamics, exploring more deeply the linkages between choices and consequences, and identifying potential strategies (demand-side management, land use practices, etc) for mitigating the effects of increasing demand and fluctuations in supply. System variables and policy options would need to be revised in consultation with island residents and local government in order to more fully calibrate the model with local knowledge, to assess potential constraints (economic and public acceptance) and to identify targets and strategies for moving forward.

## 4. Next Steps

We are working with the Islands Trust and community partners in the Gulf Islands to further refine our assessments of intrinsic vulnerability and sustainable yield, and to translate the outputs of these models into a set of guidelines that can be used in support of policy development and ongoing planning activities. As part of a follow-up project (PATHWAYS) with the Earth Science Sector of Natural Resources Canada, we are also in the process of developing an integrated modeling and decision support framework for nesting these resource assessments in the context of regional futures scenarios being developed for the Georgia Basin by the UBC Sustainable Development Research Initiative. To this end, we have begun migrating DRASTIC-Fm and STELLA© groundwater models into CommunityViz,™(Figure 8); a commercial suite of 'what-if' scenario modeling and landscape visualization tools.

The intent of the project is to leverage emerging information technologies and leading edge Canadian sustainability research initiatives to promote the uptake and use of earth science knowledge and expertise to help better address issues of public safety (risks associated with natural hazards) and resource scarcity in the context of policy development, planning and sustainable development. The coupling of web-based knowledge integration systems and scenario modeling tools offers an important avenue for exploring viable sustainable development strategies, and for building coherence in policy negotiations across jurisdictional boundaries. Uptake and use of these tools in a planning context will help promote a wider and deeper understanding of environmental, social and economic issues and offers the potential for transforming the ways in which regional urban centers and surrounding rural communities use and share information to make decisions about their collective future.

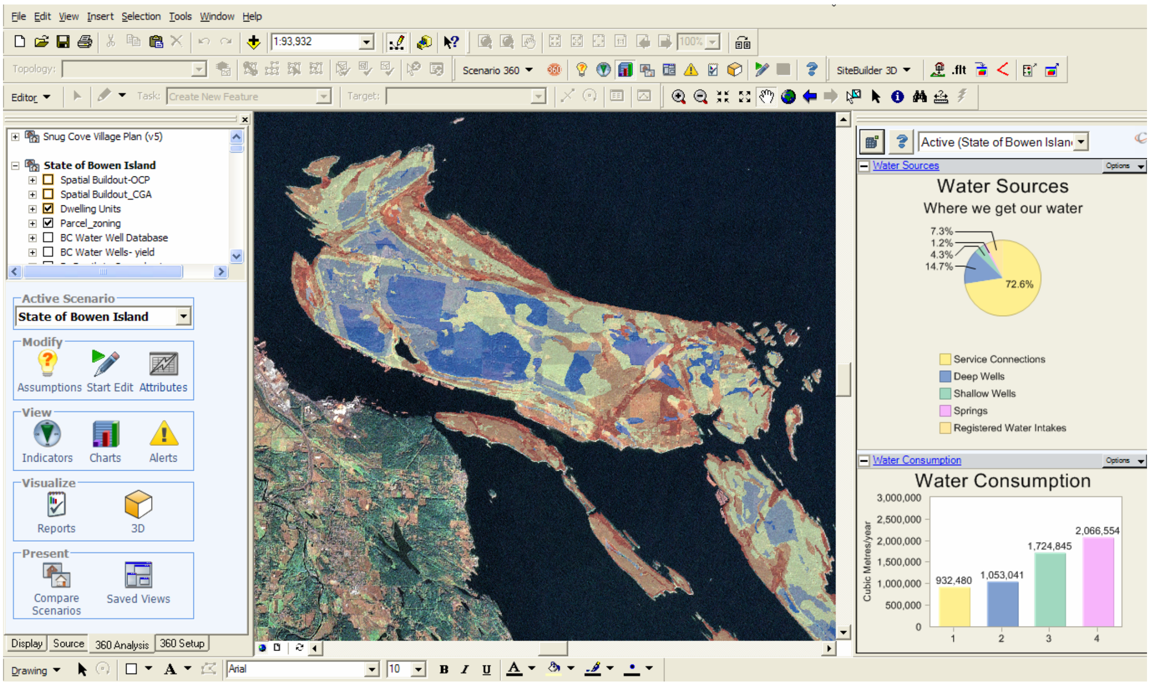


**Figure 8**: Integration of the Gulf Islands intrinsic susceptibility model within a socio-economic and planning tool – CommunityViz.

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