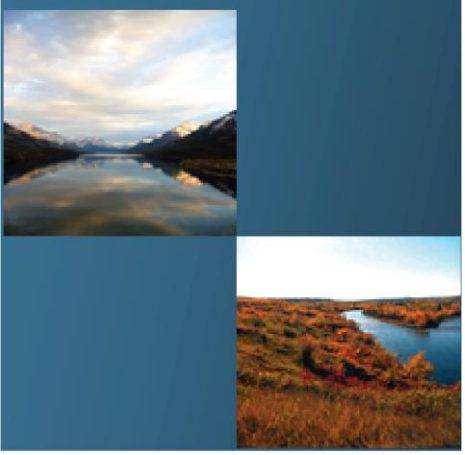
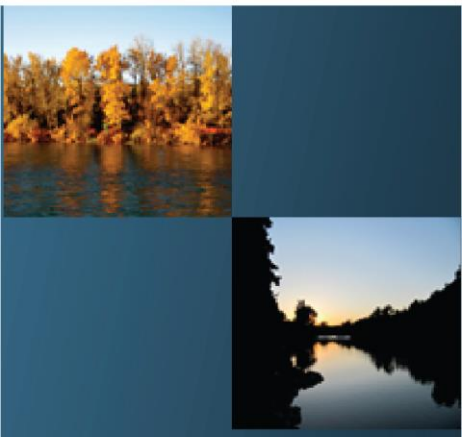


ALBERTA waterSMART Water Management Solutions



Sustainable Water Management in the Athabasca River Basin Initiative

Review of Hydrologic, River Systems, and Land Models

March 2015

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Sustainable Water Management in the Athabasca River Basin (ARB) Initiative
Phase 2 modelling tool recommendations

Overview

Model assessments were completed for Phase 2 of this initiative. The model types included: hydrological, land use, and river system models. A series of criterion were used to identify the strengths and weaknesses of each model and to determine the most suitable model for this project. Table 1 provides recommendations for models to be used in this project and a rationale for each selected model. These recommendations are intended to be in draft form are for discussion with the Core Team.

Table 1: ***Recommended models and rationale***

Recommended Model	Rationale	Additional Considerations
Hydrological **$SWAT_{bf}$**	• A version has been developed for the Boreal • It has been applied in the ARB and can be applied to the whole basin • It represents important hydrological processes and has a large development team • User support is available and it is open-source • It can be and has been linked to other models	• There may be advantages to using HGS – Suncor involvement and it is developed • GoA is using MIKE-SHE, further discussion is required to determine how MIKE-SHE is being applied.
Land use **ALCES Online**	• It has been applied in many stakeholder engagement projects and is publicly available • It has been used previously in conjunction with OASIS • ALCES Online is spatially explicit at a data- and user-defined cell size • It has a wide range of land use development scenarios already built in for the ARB and can be applied to the whole basin • It provides visual, graphical, and tabular output at a cell or watershed level that is meaningful for engagement purposes	• We are waiting for more information from the land use branch on NetLogo/Geosimulation modelling before making a final decision
River System **OASIS**	• It has been applied in other basins in Alberta • It can be applied to the whole ARB • It has been applied widely for stakeholder engagement and is publicly available • It is a robust modelling tool and can handle many river system components • It has been coupled with numerous other models • It is user-friendly, and offers substantial user support	• There are no additional considerations regarding OASIS at this time.

1. Draft Hydrological Model Review

This project will use a series of modelling tools to assess the historic and current state of the watershed, estimate a range of potential impacts on the quantity and quality of water resources from future changes in climate and land use impacts on water resources in the Athabasca River Basin (ARB), and identify a set of adaptive management options to address the current and future water-related issues in the ARB. Many of these issues are related to declining water levels, changes in streamflow regimes (flood and drought), and increases in human water use. Hydrological models provide a key component of this project, enabling estimates to be made of how the basin hydrology functions and what the anticipated streamflow responses may be to changes in the basin.

There are hundreds of hydrological models available world-wide, all of which provide some value to the user in terms of applicability to various research or management questions. This project has focused on a subset of models that have been widely applied in the North American context. This subset of models includes:

- ACRU (Agricultural Catchments Research Unit)
- CRHM (Cold Regions Hydrological Model)
- HBV-EC (Hydrologiska Byråns Vattenbalansavdelning Model)
- HEC-HMS (Hydrologic Engineering Center's Hydrologic Modelling System)
- HSPF (Hydrological Simulation program)
- HGS (HydroGeosphere)
- MIKE-SHE
- RAVEN
- RHESSYS (Regional Hydro-Eco Simulation System)
- SWAT (Soil and Water Assessment Tool)
- VIC (Variable Infiltration Capacity)
- WATFLOOD

A key objective of this review was to ensure models were applicable for the ARB Project in terms of collaborative modelling and Working Group involvement, as well as hydrological process representation (Figure 1). Hydrological process representation is important for this project given that the ARB has a complex landscape and multiple overlapping factors that can influence watershed hydrology. This review also acknowledges that there have been previous modelling studies in the ARB. This project has not examined each of these studies in detail; however, previous work is considered an asset to the ARB Project.

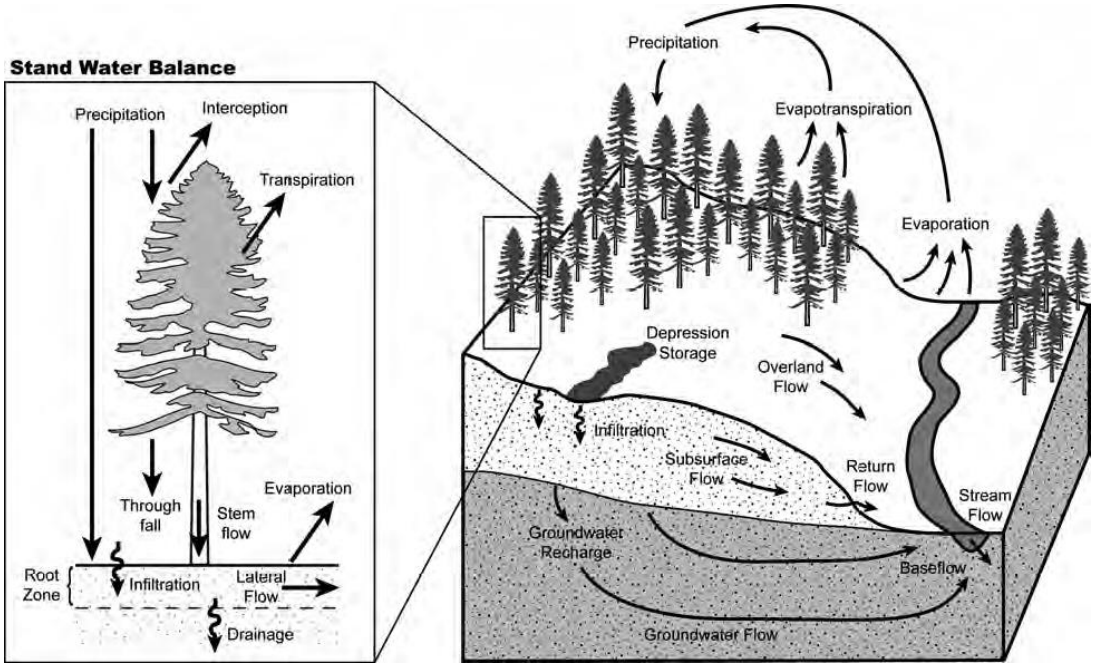

Figure 1: Example of stand-scale and watershed-scale hydrological processes (from: USGS).

Table 1: Summaries of Hydrological Models

Model	Watershed Discretization	Rain Interception	Snow Accum.	Snowmelt	Snow Interception	Sublimation	Evapotranspiration	Evaporation	Infiltration	Overland flow	Subsurf. Hill. Roff.	Groundwater Flow	Glacier Melt	Frozen Soil	Lake Storage	Peatland
ACRU	HRUs	E	E	E	E	E	P	P	E	E	E	E	E	NIF	A	Y
CRHM	HRUs	P	P	P	P	P	P	P	A	A	A	E	A	E	A	A
HBV-EC	GRUs	E	E	E	E	E	E	E	E	A	E	E	E	NA	A	NA
HEC-HMS	Sub-basins	E	E	E	NA	NA	E	E	E-P	E	E	E	NA	NA	E	E
HSPF	Lumped	E	E	E-P	E	E	E	E	E-A	E	E	E	NA	NA	A	NA
HGS	Distributed	E	E	E	Y	Y	A	A	P	P	P	P	NA	A	A-P	Y
MIKE-SHE	Distributed	E	E	E	E	E	A	E	A	P	P	P	E	NA	E	A
RAVEN	HRUs	P-F	E-F	E-P-F	P-F	P-F	E-P-F	E-P-F	E-A-F	A-F	E-F	E-F	E-F	E-F	A-F	E-F
RHESSYS	Hierarchical	E	E	A	E	E	P	P	E	E	E	E	Y	NIF	NIF	Y
SWAT	Hierarchical	E	E	E	E	NIF	E-P	E-P	E	E	E	P	Y	Y	A	A
VIC	Statistical	E	E	P	P	P	P	P	E	P	E	E	NA	E	A	E
WATFLOOD	GRUs	E	A	A	E	E	E	E	A	A	E	E	E	NA	A	E

E = empirical; A = analytical; P = physical; NA = not available in model; NIF = no information found; Y = incorporates process, but no documentation found, F = flexible and routines can easily be added.

1.1 ACRU

The agro-hydrological modelling system was originally developed in South Africa (Schulze, 1995); however, a more recent version of the ACRU model adapted at the University of Lethbridge has since included modelling routines for snow-dominated environments (Kienzle, 2008). User support is limited and there are no scheduled training sessions. A manual is available on the ACRU web page (Smithers and Schulze, 1995); however, a manual describing snow modelling was not found. There is a cost associated with the model licence.

The ACRU model is a semi-distributed, multi-layer soil model that discretizes a watershed into hydrological response units (HRU's; Schulze, 1995). The model needs a windows-based PC and typically requires extensive geospatial information system (GIS) pre-processing by linking land cover/type databases into the model and as a post-processing tool (Kienzle et al., 2010). ACRU also operates in conjunction with ACRU utilities software, which helps with preparing input and output data. ACRU Menubuilder assists the user in simplifying complex distributed watershed information (Smithers and Schulze, 1995). The source code is not readily available.

ACRU simulates several hydrological processes that are important for the ARB on a daily time step (Table 1). Total evaporation (E) includes snow sublimation, plant transpiration (T) from the rooting zone, evaporation from the soil surface, and interception. Potential E is calculated via the Penman method. Infiltration, percolation, and runoff are calculated empirically. Infiltration into the topsoil horizon and downward drainage to groundwater stores is based on user-specified soil texture, hydraulic conductivities, rooting depths, and field capacity. Runoff is routed as stormflow either as rapid response (same day as event) or delayed. Generated streamflow comprises both stormflow and baseflow, and is routed using several methods including Muskingum. ACRU can also simulate lake and wetland storage.

Key model inputs include digital elevation model (DEM), land cover classification, soil depth, and texture class map files. Meteorological data must include precipitation, minimum and maximum air temperature. Vegetation parameters include crop type, while hydraulic conductivity, soil texture, and rooting depths are required for soil parameters. Flow routing parameters include slope, length, roughness and shape. In addition to hydrologic processes outputs (e.g. hydrographs, water tables, water balances), ACRU can output sediment erosion, nutrient fluxes, irrigation, and reservoir operations.

ACRU has been applied in small to medium watersheds in Alberta, in both steep and gradual terrain. Peer-reviewed literature in Canada using ACRU simulations has been published for the St. Mary Watershed, Montana-Alberta Rocky Mountain region (Kienzle, 2010), Beaver Creek, Porcupine Hills, southwest Alberta (Kienzle et al., 2010; Forbes et al., 2011), and the upper North Saskatchewan watershed (Nemeth et al., 2012; Kienzle et al., 2012).

1.2 CRHM

The cold-regions model was developed at the University of Saskatchewan using field measurements and modelling research in prairie, tundra, and boreal environments (Pomeroy et al., 2007). Manuals are available, as well as frequently scheduled model workshops and training. There is no cost for the model licence, only an academic distribution and agreement.

CRHM is a semi-distributed model that discretizes a watershed into Hydrological Response Units (HRUs). CRHM offers a selection of process modules that allow the user to choose the model complexity depending on the user's objective, scale, and data availability. The source code is freely available to download and uses C++ language for modification. Pre- and post-processing includes GIS and Excel software. The graphical user interface (GUI) is simple and the model may be run on a PC or Mac. The source code is available and can be modified by the user.

CRHM simulates several cold-region hydrological processes on an hourly to daily time-step using physically-based equations including: snow redistribution by wind, sublimation (Pomeroy and Li, 2000), canopy snow interception, snowmelt, infiltration into frozen soils (Granger et al., 2001), hillslope water movement over permafrost, actual evaporation, and radiation exchange to complex surfaces. ET is simulated using physically-based methods (Penman-Monteith, Granger and Pomeroy, Shuttleworth and Wallace) and includes soil evaporation, plant transpiration and intercepted rainfall lost as evaporation. Methods to simulate snowmelt vary depending on data availability (energy balance model, fractal melt/depletion model, simplified melt models, or radiation and temperature index method). Soil moisture balances are empirically calculated to simulate runoff and drainage (fill and spill, saturation overland flow, shallow subsurface drainage, and groundwater drainage). Infiltration uses the Green Ampt approach and has routines for frozen soils. The model uses a Muskingum channel routing method by calculating the timing and storage of overland, interflow, groundwater flow, and streamflow. CRHM can also simulate subsurface flow through organic layers (Quinton and Balzer, 2013).

Key model inputs vary depending on the selected modules. Spatial data (basin area, DEM), meteorological data (precipitation, air temperature, net radiation, relative humidity, wind speed and direction), and vegetation data (height, albedo, and fetch distance) are typical. Land and soil characteristics including ground slope, soil thickness, bulk density, porosity, heat capacity, soil moisture conditions, and hydraulic conductivities are also needed.

CRHM has been applied in small to medium watersheds, and in steep and gradual terrain across several Canadian environments including: tundra at Wolf Creek Research Basin, Yukon (Dornes et al., 2008) and Scotty Creek Research Basin, Northwest Territories (Quinton and Balzer, 2013); prairies at Bad Lake Research Basin, Saskatchewan (Fang and Pomeroy, 2007); boreal at Prince Albert Model Forest (BERMS; Pomeroy et al., 2007); and mountain regions at Marmot Creek Research Basin, AB (Pomeroy et al., 2012; MacDonald et al., 2010). Recent application has been in the Smoky River Basin, and Smith Creek, SK (Fang et al., 2010; Pomeroy et al., 2013).

1.3 HBV-EC

The HBV-EC model is a Canadian version of the Swedish HBV-96 model (Lindstrom et al., 1997), which was modified by Environment Canada. Detailed descriptions of model algorithms can be found in Hamilton et al. (2000) and Stahl et al. (2008). There are tutorials available; however, support is limited. There is no cost to use the HBV-EC model and it has been applied in the upper Columbia River (Jost et al., 2012) and southern Alberta (Mahat and Anderson, 2013).

HBV-EC is a semi-distributed model that uses Grouped Response Units (GRUs) to group similar land cover, elevation, slope and aspect into DEM/GIS grid cells to increase computing efficiency (Stahl et al., 2008). The model allows discretization into climate zones to create bands of watershed climatology (Stahl et al., 2008). The model incorporates the Environment Canada Green Kenue™ data preparation, analysis, and visualization tool (GUI) that can integrate environmental databases and geospatial data into the model. For example, Green Kenue™ provides a graphical interface to the HYDAT database where the user can query, display, and analyze the data associated with each station. HBV-EC uses a PC operating system and relies on GIS (ArcView) software for pre- and post-processing.

HBV-EC simulated hydrologic processes on a daily time step (Table 1), which includes glacial melt processes. Within the model, runoff is routed differently from glacier versus non-glacier GRUs. Runoff from each glacier GRU is treated as separate reservoirs, while runoff from non-glacier GRUs is treated as a lumped fast-or slow-draining reservoir. The sum of outflow from fast, slow and glacier reservoirs becomes the watershed outlet streamflow. Channel routing includes a triangular weighting function or a lumped reservoir routing approach. HBV-EC calculates ET empirically from non-glacier GRUs as a function of soil moisture. Snowmelt uses a temperature index approach with the capacity to adjust the melt factor for slope and aspect. Infiltration is simulated empirically based on soil moisture storage for a given elevation band, and percolation is a function of a user specified field capacity. Groundwater flow is simulated using ‘fast’ and ‘slow’ linear reservoirs.

Key model inputs include DEM and land classification mapping (forest, open, lake, and glacier). Meteorological data includes daily precipitation, mean daily air temperature, daily potential ET, and correction factors for elevation and precipitation gauge errors. Canopy cover and interception fractions and the ratio of melt area are required vegetation parameters. Soil parameters include empirical reservoir parameters, field capacity, and lower ET limit, while channel routing requires linear reservoir parameters. In addition to typical hydrological model output, HBV-EC also provides outputs for glacial melt and lakes.

1.4 HEC-HMS

The HEC-HMS model was developed by the US Army Corps of Engineers to simulate the precipitation-runoff processes of dendritic watershed systems, particularly large river basin water supply and flood hydrology, and small urban or natural watershed runoff (Scharffenberg, 2013). Manuals are available on the model webpage and are frequently updated. There is no direct support

from the developers; however, there are example applications and training workshops available to users. There is no cost for the model licence.

HEC-HMS is a semi-distributed model that discretizes the watershed area into hydrologic elements (sub-basin, reach, reservoir, junction, diversion, source, sink) connected in a river network. HEC-HMS uses PC, Oracle Solaris, and Linux operating systems. The model has an integrated system of several parts that include a database, data entry utilities, computation engine, data storage system, and results reporting tools, which can be easily navigated using the GUI. Other software for model application includes GIS (ArcView) or HEC-GeoHMS. The model code is open source.

Hydrologic processes are simulated on sub-daily or greater time steps (Table 1). Snow processes include a temperature index-based snowmelt model. ET is calculated either as a monthly average to incorporate measured data (e.g. pan evaporation or eddy covariance) or Priestly-Taylor, and is a function of soil water moisture. Infiltration can be simulated via various methods including a constant or exponential rate, SCS curve number, Green-Ampt, or Smith-Parlange. Excess precipitation is calculated into surface runoff using unit hydrograph methods (Clark, Snyder, SCS technique) and Kinematic wave. Open channel flow routing options include simple time lag, Kinematic wave, Muskingum routing, modified Puls method, straddle stagger method, loss-gain method, and Muskingum-Cunge method for complex channel geometry. The model can incorporate lakes and reservoirs, as well as in-stream vegetation and wetlands. Additional analysis tools include parameter estimation, depth-area analysis, flow forecasting, erosion and sediment transport, and nutrient water quality (Scharffenberg, 2013).

Data input required for HEC-HMS depends on model complexity. The model includes a meteorological model component that performs a data analysis using shortwave radiation, precipitation, ET, and snowmelt data for continuous simulations. Vegetation parameters include crop coefficients, while linear reservoir parameters for interflow and baseflow storage are required soil parameters.

HEC-HMS has been applied worldwide, particularly for watershed runoff (e.g. Menberu et al., 2014) and flood forecasting applications, and has been applied in the northwestern USA (Kinoshita et al., 2014; Tripathi et al., 2014).

1.5 HSPF

The HSPF model was developed by the US Geological Survey to represent the model area as pervious and impervious land areas, stream channels, and mixed reservoirs (1D simulations). HSPF has been used worldwide with recent application in the ARB (Golder Associates Ltd, 2009). A manual is available on the model webpage, and tutorials are included in the HSPF manual (Windows help file). There is no cost for the model licence. Support may be possible through a USGS HSPF user list server.

The model is semi-distributed, and discretizes a watershed into HRUs (Bicknell et al., 2001). HSPF operates using Unix or DOS. The model has a fully integrated windows-based GUI, Gen Scn that allows the user to run the model and analyze model output. The model also includes the WDMUtil

tool that manages watershed modelling time-series data (e.g. meteorological data). The code is not open source.

Hydrologic processes are simulated on a variable time step, but typically hourly (Borah and Bera, 2003). Snowmelt can be simulated via the temperature-index method or an energy balance method. Actual ET is calculated empirically as a function of potential ET inputted by the user, soil moisture availability and ponded water. Infiltration is based on infiltration capacity curves. Surface runoff is calculated empirically relating excess water and detention storage using the Chezy-Manning equation for flow. Subsurface flow is simulated empirically using non-linear equations. All inflows are assumed to enter at an upstream point and outflows are a function of reach volume. The model also has the ability to simulate water quality (sediment, nutrient, pesticide, and chemical parameters).

Key data input includes DEM and classification of pervious and impervious land segments with similar hydrological characteristics. Minimum meteorological data include precipitation and air temperature; however, meteorological data requirements increase if using the energy balance snowmelt equation. Vegetation data includes canopy interception capacity, canopy cover, potential ET, Manning's roughness coefficients, while soil characteristics such as porosity and storage capacity are needed along with values for infiltration equations, interflow, and groundwater recession curves.

HSPF has been used worldwide with recent application in the ARB (Golder Associates Ltd, 2009). Golder Associates Ltd. (2009) selected HSPF from a number of hydraulic models to assess potential effects of climate change on water yield in the Athabasca River up to Fort McMurray, the Beaver River up to the Alberta border, and the Firebag River.

1.6 HydroGeoSphere

HydroGeoSphere (HGS) was developed by researchers at the University of Waterloo (Ontario), Université Laval (Québec), and HydroGeoLogic, Inc. (Virginia) as a fully integrated surface water-groundwater model. The manual has recently been updated (Aquanty Inc., 2013). A HGS user forum was launched in early 2013 on the HGS webpage and support is available through the model webpage. There are short courses available, but not frequently offered. There is no cost for the model licence, only an academic distribution and agreement.

HGS is a distributed, physically-based model composed of a modified Surface Water Flow Package from the MODHMS model, fully-integrated into the 3-D variably-saturated groundwater flow model (FRAC3DVS). HGS code is written in the FORTRAN computer language. The HGS package consists of three components: 1) a preprocessor that converts user input into the simulator format, GROK; 2) the simulator; and, 3) a post-processor, HSPLOT.

Hydrological processes of HGS are simulated on a variable time step (

Table 1). Rainfall that is partitioned into overland and channel flow is simulated using a 2-D, depth-averaged diffusive-wave approximation of St. Venant flow equations. Winter processes were recently added to the model (Aquanty Inc., 2013). Snowmelt is simulated via the temperature-index method. ET removes water held in canopy interception, water on the soil surface, or uptake of soil water from the vegetation root zone. Actual ET is modelled using an empirical algorithm for transpiration (Kristensen and Jensen 1975) and evaporation from the surface and subsurface. Potential ET measurements can be derived from pan measurements or vegetation and climatic factors (e.g. Penman-Monteith or Hamon methods). Infiltration rates are calculated internally by the model using van Genuchten (1980) characteristic curves. The 3-D variably saturated subsurface flow is calculated with a modified form of Richards' equation. The influence of fractures and macropores on subsurface processes can also be included in simulations.

There are several key data inputs given the complexity of the model. Spatial mapping data including DEM, geologic layering, and vegetation cover are needed. Meteorological data includes precipitation and data needed to calculate potential ET, which is done outside model simulation. Vegetation parameters include leaf area index (LAI), field capacity, wilting point, oxic and anoxic limits, interception value, root density function, root depth, and fitting parameters. Soil parameters include hydraulic conductivity, specific storage, porosity, anisotropy ratio and soil moisture curves. Routing parameters include Manning's N, microtopography height, and minimum mobile water depth.

HGS is applied from field plots to large watersheds. For example, Li et al. (2008) simulated the hydrologic response in a 300 km^2 watershed in the Boreal Shield driven by multi-season precipitation events. HGS has been applied in the Boreal Plain to understand groundwater recharge and water table dynamics in harvested landscapes (Carrera-Hernandez et al., 2011), as well as soil water dynamics and the influence of cover thickness on the reclamation of forest lands in the ARB (Carrera-Hernandez *et al.*, 2012).

1.7 MIKE-SHE

The MIKE-SHE model was developed by three European organizations (Système Hydrologique Européen, [SHE]; Abbot et al., 1986a, b) and the full model is currently distributed by the Danish Hydrological Institute (DHI). The model is used to simulate components of the hydrologic cycle, sediment, nutrient and pesticide transport, water use and management options (irrigation systems, pumping wells, water control structures, and reservoirs), and agricultural practices. There is a manual available including tutorials and training workshops. Model licences range from $8,000 to $28,000 depending on the version licence, which can include the river-based model MIKE-11. There are also annual maintenance fees ($3,500 to $4,800).

MIKE-SHE is a deterministic, fully-distributed model that discretizes the model area into grid squares from centimetres to hundreds of meters. Data preparation and model set-up can be completed using a PC operating system, GIS (ArcView), or MIKE SHE's built-in GUI pre-processor. The model has a digital post-processor for model calibration and evaluation. The source code is not available.

MIKE-SHE simulates hydrologic components including movement of surface and unsaturated subsurface water, ET, overland channel flow, saturated groundwater flow, and exchanges between surface water and groundwater on a user-specified time step (Graham and Butts, 2005). Snowmelt is calculated using an empirical degree-day method. ET from vegetation and soil is calculated using the analytical Kristensen and Jensen (1975) method or a two-layer water balance method, both a function of LAI, root zone properties and ponded water. Precipitation as throughfall or snowmelt can either infiltrate or runoff as overland flow. Infiltration can be simulated using four options: Richard's equation, gravity flow as a simplification of the Richard's equation, two-layer water balance method, or net recharge input. Runoff is calculated using a finite-difference, diffusive-wave approximation of the Saint-Venant equations or using semi-empirical approach based on the Manning's equation. Saturated groundwater flow is modelled using a fully-implicit, 3-D finite difference scheme or a conceptual, linear reservoir method. MIKE-SHE can use MIKE-11 to simulate channel flow (Havno et al., 1995), and supports several methods including diffusive-wave, Kinematic wave, quasi-steady state approximations, Muskingum or Muskingum-Cunge methods.

Similar to HGS, MIKE-SHE requires several inputs given model complexity. Some key inputs include DEM, soil type, geologic layering, and vegetative cover mapping. Air temperature, precipitation and potential evaportranspiration (PET) are required for meteorological data. Vegetation parameters include LAI, field capacity, wilting point, interception value, root zone depth, and fitting parameters, while hydraulic conductivity, specific storage, porosity, and anisotropy ratio are needed for soil parameters.

MIKE-SHE is applied at a variety of spatial scales and has no limitation on watershed size. The model has been used to simulate hydrologic processes worldwide in a variety of environments. For example, Wijesekara et al. (2010) coupled MIKE-SHE/MIKE-11 with a land-use model to assess the impact of future land-use changes on hydrological processes in the Elbow River watershed in southern Alberta. Furthermore, Alberta's ESRD is currently developing a MIKE-SHE model for the South Athabasca Oil Sands region (Kargbo, Pers. Comm.)

1.8 Raven

Raven was recently developed at the University of Waterloo (Craig et al., 2013) as a flexible tool that can be customized to understand the hydrological behaviour of a watershed and assess the potential impacts of land use, climate, and other environmental change on watershed properties such as flood potential, soil water availability, or groundwater recharge. The model can be used to investigate individual storm events or develop long-term water and energy balances for resource management. Raven is an open-sourced model; therefore, there is no cost for the model licence. There is a user and development manual available, but there are currently no tutorials or workshops. In addition, Raven is a relatively new hydrologic model; therefore, peer-reviewed application of watershed modelling is limited.

Raven is unique, primarily due to its numerical robustness and its flexibility from a single watershed lumped model to a full semi-distributed system. HRUs are used to discretize the model area into similar hydrologic function. Raven is able to use a wide variety of algorithms to represent each

component of the hydrological cycle. This provides access to a number of different methods of interpolating meteorological data, routing water downstream, and representing hydrological processes within this modelling framework (Craig et al. 2013). Raven's flexibility and large library of user-customizable subroutines allow it to emulate a number of existing hydrological models. Raven has achieved near-perfect emulation of the UBC Watershed Model (Quick, 1995) and Environment Canada's version of the HBV model (Bergstrom, 1995). Conceptual emulation is available for various algorithms used within Brook90, SWAT, VIC, PRMS, HYMOD, and WATFLOOD (Craig et al. 2013). Multi-model emulation allows us to compare multiple models within one package, enabling a high degree of confidence in model outputs. Raven is also setup to use the Environment Canada Green Kenue™ tool; this allows for a wide range of hydrologic analyses to be conducted in an efficient manner. Model developers recommend Ostrich, an independent multi-algorithm optimization and parameter estimation tool that can be used to calibrate Raven models and generate Monte Carlo simulations (Craig et al., 2013).

Data input required for Raven depends on the model complexity or availability of data. For a simple, lumped watershed only daily precipitation and air temperature are required to simulate streamflow, while discretization into thousands of HRUs per sub-basin will require additional parameters (e.g. hourly longwave radiation, wind velocity, and air pressure; Craig et al., 2013).

1.9 RHESSys

The RHESSys model was developed by the University of California, Santa Barbara as an ecohydrological model. The model is GIS-based that integrates water, carbon and nutrient dynamics as well as vegetation growth at watershed and regional scales (Tague and Band, 2004). A manual is available (Tague and Band, 2004) as well as user documents on the model webpage; however, there is limited support. There is no cost for the model licence.

RHESSys partitions the landscape using a hierarchical approach using hydrologically distinct units: patches (similar soil and land use), hillslopes (contributing areas that drain to a stream reach), climate zones and watersheds (to organize stream routing). The model computes connectivity and lateral hydrologic fluxes between landscape units within a watershed. RHESSys operates using a PC, and requires GIS software. The source code is available to users.

Hydrological processes are simulated on a daily time step (Table 1). Snowmelt is calculated using an adaptation of a degree day approach to include radiation and rain-on-snow energy fluxes. ET is computed using the Penman-Montieth method, and includes evaporation of canopy interception, snow sublimation, evaporation from soil and litter stores, and leaf transpiration. ET varies with soil water availability, vapor pressure deficit, atmospheric CO^2 concentration, radiation and air temperature by using a stomatal conductance model (discussed in Garcia and Tague, 2014). Infiltration is simulated via the Phillips infiltration equation, while percolation is dependent on field capacity. If detention storage is filled in the grid (e.g. patch), then overland flow is simulated dependent on grid size. The model routes laterally and each grid can receive additional moisture inputs based on a soil water balance. Surface and subsurface lateral flow can be routed using either the quasi-spatially distributed model, TOPMODEL (Beven and Kirkby, 1979) or via an explicit water-

routing algorithm; a function of surface topography, surface, soil and drainage characteristics. Deep groundwater stores are drained to the stream using a simple linear reservoir (Garcia and Taque, 2014). Streamflow routing can be generated by a GIS-based preprocessing routine to create flow topology, forced using a stream network file, or with a unit hydrograph.

Key model input for RHESSys includes DEM, soil and vegetation mapping files. Meteorological, vegetation, and soil parameters include, but not limited to, minimum and maximum air temperature, precipitation, interception capacities, infiltration index, and time of storage index.

RHESSys has been applied to small to medium watersheds. The model has been applied throughout the USA (e.g. Tang et al., 2014a), including northwestern USA. For example, Garcia and Taque (2014) examined evapotranspiration differences in three headwater watersheds located in Colorado's Rocky Mountains, Oregon's Western Cascades, and California's Northern Sierra Nevada.

1.10 SWAT

SWAT was developed by the Texas A&M University and USDA Agriculture Research Service as a watershed-scale model to assess land management practises on water resources and nonpoint source pollution problems (Neitsch et al., 2005; Gassman et al., 2007). SWAT was designed for long term yields rather than single flood events (Arnold et al., 2008). The SWAT model was adapted to the Canadian Boreal Plain at the Swan Hills research watershed, Alberta, as part of the Forest Watershed and Riparian Disturbance (FORWARD). $SWAT_{BF}$ better represents hydrological processes important to boreal forest watersheds (Watson and Putz, 2013). Manuals, online tutorials, and paid workshops are available. There is no cost for the model licence.

The semi-distributed model can be applied to small or large watersheds. A watershed is divided into multiple sub-watersheds that are further subdivided into HRUs consisting of homogeneous land use, management, topographical and soil characteristics. Several GIS interface tools have been created alongside the development of SWAT including SWAT/GRASS, IOSWAT, and ArcView-SWAT. IOSWAT includes the Topographic Parameterization Tool (TOPAZ), Sub-watershed Spatial Analysis Tool (SUSAT), and OUTGRASS are used to delineate sub-watershed maps and HRU discretization. The model operates using a PC or Unix work station and the source code is available in the FORTRAN computer language.

The SWAT model simulates hydrologic processes for each HRU on a daily time step. The model is also capable of continuous simulation over long periods (1 to 100 years). Snowmelt is estimated based on a temperature-index approach within elevation bands to account for orographic precipitation. Potential ET is estimated via several methods including Penman-Monteith, Priestly-Taylor, and Hargreaves. ET values can also be calculated externally and used as model input. Analytical methods are used to calculate soil moisture redistribution, runoff, and groundwater flow (Neitsch et al., 2005). SWAT estimates surface runoff using the NRCS Curve Number method or Green-Ampt. The model can include processes such as preferential (bypass) flow and perched water tables (Neitsch et al., 2005). Groundwater recharge below the soil profile is partitioned between shallow and deep aquifers. The shallow aquifer can return flow to the stream or plant ET, while deep

aquifer recharge is assumed lost from the system. Flows from all sub-watersheds are summed and then routed through the stream system using the variable rate storage method or Muskingum method, both variations of the kinematic wave approach (Gassman et al., 2007). Water can be routed through channels, ponds, wetlands, depressional areas, and/or reservoirs to the watershed outlet. The model also contains components to simulate nutrient cycling, sediment yield and water quality.

Specific modification to the SWAT model for the boreal forest version includes removal of the plant growth and management practices component of SWAT to make it more suitable to forested watersheds, rather than agricultural crops (Waterson and Putz, 2013). Algorithms that account for the effects of slope and aspect on incoming solar radiation, water storage in the litter layer, anisotropy in soils, percolation limits as a function of textural discontinuities with depth, winter groundwater storage in small streams, bogs and fens, the Oudin method for potential ET, and HRU connectivity have also been added to better represent the Boreal Plain processes.

SWAT has been applied in a diverse range of watersheds worldwide (Gassman et al., 2007), as well as in the ARB (e.g. Abbaspour et al., 2010). However, the $SWAT_{BF}$ version is most applicable to the ARB (Watson and Putz, 2013).

1.11 VIC

The VIC model was developed by University of Washington to solve full water and energy balance equations (Liang et al. 1994). The model is used for large-scale applications and can be coupled with global circulation models to assess the effects of climate change. There is no manual; however there are several webpages of instruction and published articles available on the model webpage (e.g. Liang et al., 1994). Support is limited; however, there is a VIC user support list.

VIC is a macroscale model with statistical representation of sub-grid variability (i.e. snow elevation bands, fractional coverage of soil and vegetation types). The land surface is modelled as a grid of large (>1 km or 1/8 to 2 degree latitude by longitude), flat uniform cells. VIC operates using UNIX, freebsd, Linux, and DOS systems. Model code is open source and frequently updated. GIS (ArcInfo) and Gnu C-compiler (freeware) are used for pre-and post-processing.

Model simulations are done on a sub-daily time step. Snow accumulation and melt are simulated using a combined energy- and mass-balance approach. ET includes energy-based calculations for vegetation and soil (i.e. Penman-Monteith) including canopy interception evaporation. Spatial variability of infiltration and runoff generation is simulated using the variable infiltration curve (Liang et al., 1994), while baseflow is represented using the empirically based Arno baseflow curve (Liang et al., 1994). Streamflow is estimated at a specified location by routing runoff and base flow from each grid cell using the method of Lohmann et al. (1998).

At a minimum, VIC requires air temperature and precipitation as meteorological data input. VIC requires DEM, land cover and soil type mapping. Several constants including rain/snow temperature thresholds, snowpack roughness, and sub-grid precipitation variability are needed. Key vegetation

input includes LAI, and ET indices (e.g. wind attenuation, minimum stomatal resistance). Soil parameters include infiltration curves, baseflow exponents, hydraulic conductivities, soil characteristics (e.g. field capacity, wilting points, and bulk densities). A flow direction file is needed for channel routing.

Further development of VIC has has been focused on increasing its applicability in snow-dominated environments including simulating frozen soils (Cherkauer and Lettenmaier 1999; Cherkauer et al., 2003), blowing snow (Bowling et al., 2004), lakes and wetlands (Bowling et al., 2003). VIC has been applied in the ARB, most recently by Eum et al. (2014) to assess the uncertainties in annual/seasonal streamflow and annual peak flow simulations with respect to selection of climate data and model parameter sets.

1.12 WATFLOOD

The WATFLOOD model was developed at the University of Waterloo and is aimed at flood forecasting and long-term hydrologic simulation using distributed precipitation data from radar or numerical weather models (University of Waterloo, 2001). There is a manual available on the model webpage, which also includes example data and some instruction; however, there are no tutorials available and support is limited. There is a cost for the model licence; however, prices were not available at the time of reporting.
The semi-distributed model is typically applied with grid sizes from 1 to 45 km^2 and for watershed areas from 15 to 1,700,000 km^2 (Kouwen, 2008). A watershed may be discretized into kilometre scale grids, and then subsequently divided into GRUs with similar characteristics, which are summed for each grid. The model uses a PC operating system and is written in the FORTRAN language. Model code is not open source. WATFLOOD uses a GUI programmed in MS Visual Basic for Windows. The model can also be linked into the Environment Canada Green Kenue™ tool, similar to HBV-EC and Raven. WATFLOOD optimizes the use of spatially referenced (GIS) resources including remotely sensed data, radar-rainfall data, LANDSAT, or SPOT land use or land cover data. Microsoft Excel or Grapher are used for post-processing. Simulation typically takes approximately one minute to run for a 50,000 km^2 watershed with a 10 km grid, one-year simulation, and hourly time steps on a 800 Mhz Pentium III™ (University of Waterloo, 2001).

Hydrologic fluxes are simulated on an hourly time step (

Table 1). Snowmelt is calculated using a temperature-index approach or an analytical radiation-temperature approach. Potential ET is estimated using Preistley-Taylor or Hargreaves, actual ET is estimated as a function soil moisture, soil temperature, vegetation type, and canopy interception. Infiltration is calculated using an analytical Green-Ampt infiltration model. When infiltration capacity is exceeded and detention storage filled, stormflow is generated based on a Manning formula. Baseflow is estimated by applying a power function to a measured stream hydrograph at the watershed outlet. The summation of runoff, interflow and baseflow are added to the channel flow from the upstream grids and routed through the grid to the next downstream grid using a storage routing technique.

Key required inputs for WATFLOOD include DEM map files. Air temperature, rain/snow gauge (radar data), and radiation data are key meteorological data inputs. Vegetation parameters include forest vegetation coefficients for actual evapotranspiration (AET) estimates, and interception fractions, while soil parameters include empirical values, soil moisture and temperature coefficients for AET estimation, depth and resistance of the interflow layer.

WATFLOOD has been used to model watersheds such as the Mackenzie (Soulis and Seglenieks, 2008), Great Lakes (Pietroniro et al., 2007), and South Saskatchewan river basin (Lapp et al., 2009). The model has been applied in the Peace and Athabasca regions (Pietroniro et al., 2006; Toth et al., 2006). For example, Toth et al. (2006) used the model to investigate the relative roles of climate variability and flow regulation at the confluence of the Peace and Athabasca Rivers.

1.13 Model Ranking

A model ranking scheme was developed to compare the selected hydrological models to various evaluation criteria. The models were ranked numerically based on nine categories described below:

1. Licence Cost – price of the model and maintenance fees. Rank: [0-2]; 0 for expensive (>$5,000), 1 for moderate (<$5,000), and 2 for no cost. Expenses related to technical support were not included.
2. Computing / Speed – time and effort needed for computing model simulations. Rank: [0-2]; 0 for high, 1 for medium, 2 for low.
3. Data Requirements – number of required input data. Rank: [0-2]; 0 for high, 1 for medium, and 2 for low.
4. Model Integration – studies available that indicate integration with other models. Rank: [0-2]; 0 for never, 1 for one study, and 2 for two, 3 for extensive studies (3 or more).
5. Link Environmental Databases – i.e. Hydat. Rank: [0-1]; 0 for no, 1 for yes.
6. Key Hydrological Processes – model simulates all key processes. Rank: [0-10]; 10 for all 15 processes. It was deemed that peatlands, snow hydrology, and groundwater flow are key components of the boreal hydrological setting; therefore, 2 points are lost for each process not simulated within this group. The model lost 1 point for not simulating any of the other processes. The same number of points were also lost if there was insufficient information available to determine how the model represented each process.

7. Spatial Scale – for what watershed size the model was developed or recommended to be used [Application scale (from Beckers et al., 2009): small (<100 km^2); medium (100 - 10,000 km^2); large (>10,000 km^2) Rank: [0-1]; 0 for small to medium, 1 for large. A larger watershed application scale was ranked higher due to the size of ARB.
8. Technical Support and Documentation – support available for the model including manuals, web pages, tutorials (sample runs), and workshops. Rank: [0-2]; 0 for limited (web pages only), 1 for manual and either tutorials or workshops, and 2 for well documented and supported.
9. Applied in ARB – studies published with model simulations in ARB. Rank: [0-1]; 0 for no, 1 for yes.

The total score gives the sum of all ranked criteria out of 24. The categories and associated points for each model are presented in Table 2.

Table 2: Model ranking relative to five key categories

Category	ACRU	CRHM	HBV-EC	HEC-HMS	HSPF	HGS	MIKE-SHE	RAVEN	RHESSYS	$SWAT_{bf}$	VIC	WATFLOOD
Licence cost (Max = 1)	1	1	1	1	1	0	0	1	1	1	1	1
Computing / Speed (Max = 2)	1	2	1	0	0	2	0	2	1	2	1	1
Data Requirements (Max = 2)	2	1	2	2	2	1	2	2	2	2	2	2
Model Integration (Max = 3)	1	2	3	3	3	1	3	1	1	3	3	3
Link Environmental Database (Max = 1)	0	1	1	0	0	0	0	1	0	1	0	1
Key Hydrological Processes (Max = 10)	7	10	7	4	6	7	1	10	8	8	9	9
Spatial Scale (Max = 2)	2	1	2	2	2	2	2	2	1	2	1	2
Tech. Support & Documents (Max = 2)	1	1	1	2	2	2	2	2	1	2	1	1
Applied in ARB (Max = 1)	1	0	0	0	1	1	1	0	0	1	0	1
Total (Max = 24)	**18**	**19**	**19**	**16**	**18**	**17**	**19**	**21**	**15**	**22**	**18**	**21**

The highest scoring model was $SWAT_{bf}$, with WATFLOOD and RAVEN scoring a close second. The factors separating models were primarily the model's previous application in integration and hydrological process representation. Previous application in an integrated modelling exercise was determined

through a desktop review of previous projects published online. This review suggests that $SWAT_{bf}$ is the most appropriate model for application to the ARB Project. Further work is required to determine how each model could be applied in a collaborative manner, this will work will be conducted through interviews with model developers. It is also important to consider that models that have previously been applied in the ARB may offer an opportunity to build from existing work. This factor was given a relatively low weight in the model ranking given that previous application in the ARB does not preclude applicability in the ARB. For additional details and tables on the hydrological model review please refer to Appendix A of this document.

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2. Draft Land Use Model Review

Land use plays an important role in governing water quantity and quality in Alberta, and is of central importance to the maintenance of healthy terrestrial and aquatic ecosystems. The way in which we use the landscape can have a substantial effect on water quality and quantity (Alberta ESRD, 2015); therefore, accounting for these effects through land use modelling is an important aspect of this project. Land use models are being explored in terms of their ability to quantify land use change, leading to an assessment of water quality and quantity effects from land use development and natural disturbance scenarios. Ideally a land use model would be applied to simulate best management practices and test scenarios in real time in a collaborative setting.

Numerous land use models exist, many of which have been widely used and tested in a North American context. This report provides an in depth review and comparison of the land use models listed below:

- ALCES (A Landuse Cumulative Effects Simulator)
- LTM (Land Transformation Model)
- SELES (Spatially Explicit Landscape Event Simulator)
- CanWET (Canadian Watershed Evaluation Tool)
    - Note: CanWET is not explicitly a land use model; however, has some land use functionality. Therefore, it is included in this assessment.
- NetLogo (GeoSimulation)
    - Note: Net Logo is not explicitly a land use model; however, it's tailored use in the SAORSA has land use functionality. Therefore, it is included in this assessment.
- TELSA
- What if?

In order for a land use model to be applicable for the ARB Project it should be spatially explicit and enable analysis at functional resolutions to simulate meaningful change relevant to water resources. It should be mathematically based and incorporate as many land use categories as possible. Simulation of alternative management scenarios is beneficial for assessing the efficacy of environmental management plans. It is also important that the model be able to actively engage working group participants, as this is a key element of the project. This model review attempts to isolate a fit for purpose, spatially explicit, integrated, and user-friendly land use model that is applicable to the ARB while satisfying the following selection criteria:

1) The model must be publically available
2) It must not require an extensive degree of technical support
3) It must have an appropriate level of computing requirements
4) It must run at functional spatial and temporal scales (user-defined spatial resolution and monthly or smaller time steps)

5) It must have the potential to link to other models
6) It must incorporate the required land use modelling components
7) It must be user friendly
8) It must have some previous use in the ARB or similar landscapes

This review also attempts to highlight a model that will satisfy the objectives of the ARB project as specified below:

- Provide an understanding of potential impacts to streamflow from land use changes, and an understanding of how potential changes in land, climate, and water management plans may impact water users, water quality, and water needs for aquatic resources.
- Use a collaborative modelling process to evaluate mitigation strategies and options to identify risks for various future scenarios based on existing and new developments, environmental, and land use and climate change.

Table 3 provides a summary of the land use model review. Additional tables and details from the land use model review are available in Appendix B of this report. The remainder of this report describes the models currently under consideration and ranks them according to their application to the ARB Project.

Table 3: Land use model summary

MODEL NAME	ALCES Toolkit	LTM	SELES	CanWET	NetLogo (GeoSimulation)	TELSA	What if?
MODEL TYPE	Cell based modelling with multiple components	Neural network based	Raster based model using probabilistic disturbance spreads	GIS based watershed management tool with land-use functionalities	Agent based modelling	GIS based landscape model of vegetation dynamics	GIS based planning support system
LICENSE COST	None	None	Not specified	Not specified	None	None	None (model support is an extra charge)
COMPUTING							
Hardware and software requirements	GIS, PC, Stella, Excel	PC, GIS, Excel, MS Access	PC, PampaGIS, FRAGSTAT	PC, MapWindow	Cross platform, QuickTime, GIS	PC, ArcGIS, VDDT	PC, Windows OS, ArcGIS
GUI	Yes	None	Yes	Yes	Yes	Yes	Yes
Operating System	Windows or Macintosh	Windows	Windows	Windows	Windows or MacIntosh	32-bit OS (Windows 2000 or Windows XP)	Windows
Publicly available	Yes	Yes	Not specified	Not specified	Yes	Yes	No
Link Environ. Databases	Linked to Historical Alberta Land Use Footprint (www.abll.ca)	Not specified	Not specified	Yes	Not specified	Not specified	No
Simulation Time	minutes	minutes	~10 minutes	minutes	Minutes	minutes	minutes

MODEL SCALE							
Time Step	Variable	Variable	Variable	Daily	Variable (Current SAOSRSA model is annual)	Decades / Centuries	Yearly or greater
Spatial Scale	Variable	Variable	Variable	Variable	Variable	Regional landscape	City to regional
Finest Spatial Resolution	Anything data can support	Anything data can support	Anything data can support	Provides output results at watershed level	Anything the data can support	Anything the data can support	Anything data can support
MODEL INTEGRATION ABILITY							
Model integrated with others	Yes (With OASIS, EwE (CSIRO in AU)	No	Yes (With Mountain Pine Beetle Model)	Not specified	Yes	Possible via GIS platform	Not specified
KEY NATURAL DISTURBANCES	**ALCES Toolkit**	**LTM**	**SELES**	**CanWET**	**NetLogo (GeoSimulation)**	**TELSA**	**What if?**
Fire (constant, random)	Y, Y	Not specified	Y, Y	Not specified	Y, Y	Y, Y	Not specified
Insects (constant, random)	Y, Y	Not specified	Y, Y	Not specified	Y, Y	Y, Y	Not specified
Climate Change (constant, random)	Y, Y	Not specified	N, Y	Y, N	Y, Y	Y, N	Not specified
KEY LANDUSE TYPES AND LANDSCAPE CHANGES							

Natural disturbance	Y	Not specified	Y	Not specified	Y	Y – for vegetation dynamics	Not specified
Forestry	Y	Y	Y	Y	Y	Y	Y
Energy Sector	Y	Not specified	Not specified	Not specified	Y	Not specified	Y
Mining	Y	Not specified	Y	Y	Y	Not specified	Y
Municipal development	Y	Y	Y	Y	Y	Not specified	Y
Agriculture	Y	Y	Y	Y	Y	Not specified	Y
Water Metrics	Y	Y	Y	Y	Y	N	Not specified
Other…	any data supported by GIS	any data supporte d by GIS	any data supported by GIS	Any data supported by GIS	any data supported by GIS	Successions and natural disturbances	Any data supported by GIS
STAKEHOLDER ENGAGEMENT							
Graphical output?	Y	N	N	Y	Y	Y	N
Map output?	Y	Y	Y	Y	Y	Y	Y
Incorporate stakeholder opinion on the fly?	Y	N	N	Not specified	Not specified	Not specified	Not specified

EASE OF USE IN ARB	ALCES Toolkit	LTM	SELES	CanWET	NetLogo (GeoSimulation)	TELSA	What if?
Degree of in-house technical support required	Moderate	Extensive	Moderate	Limited	Moderate	Moderate	Moderate
Past use in ARB?	Y	N	N	N	Y	N	N

2.1 ALCES

ALCES (A Land Use Cumulative Effects Simulator) was developed by ALCES Landscape & Land-Use Ltd (ALCES Group, 2013). The ALCES Toolkit includes desktop components (ALCES Integrator and Mapper) for completing land-use simulations and a web application (ALCES Online) for visualization and customization of the simulations. This model toolkit has a detailed user manual as well as video tutorials, training workshops, and extensive user support (ALCES, 2010b). The cost of the ALCES Toolkit is primarily the server cost to deliver the ALCES Online application. This server cost would be waived for the ARB Project (B. Stelfox pers. Comm.).

The ALCES Toolkit is a landscape simulator that can be governed by historical, current or user-defined rates of land use development; it runs on either Microsoft Windows Operating System or Mac Operating System. ALCES Integrator uses stock and flow algorithms in the STELLA modelling platform to simulate regional land-use dynamics and ALCES Mapper uses a GIS platform to spatially allocate activities and track changes for spatially explicit cells. This integrated modelling approach makes it possible to efficiently complete spatially explicit simulations for large landscapes. Simulation outcomes from Mapper can be uploaded to ALCES Online, a web application that is designed to allow individuals without a modelling background explore simulations and extend their utility through the development of new indicators and scenarios. ALCES is not an open source model because the code is locked to prevent any inadvertent modifications (ALCES Group, 2013), resulting in an easy to learn model with no prior coding knowledge required. The ALCES Toolkit has been recently developed to enable full flexibility for unique application as defined by the user. ALCES code is available upon request for license holders who wish to modify it.

ALCES Mapper and ALCES Online are fully developed spatially explicit models that generate maps of land use and landscape change. ALCES Mapper functions at a range of user-defined cell sizes, while ALCES Online functions at either 2.5km^2 or 5km^2 cell resolution. A new version of ALCES Online is being developed at 1 km^2 for the province of Alberta. It is not directly linked to any external databases in Alberta; however, this feature is also currently under development. ALCES supports a variety of input data types including forestry, cropland and livestock, hydrocarbon and mining, transportation, tourism and recreation, human population, urban design, protected areas, meteorology, climate change, air emission, hydrology, natural disturbance, plant community dynamics, carbon pool dynamics, wildfire dynamics and wildlife population dynamics (ALCES Group, 2013). ALCES also supports user-defined inputs.

ALCES Integrator can be applied at daily, weekly, monthly, or annual time scales and over a range of user-defined spatial scales; however, it is generally customized for regional landscapes (50,000 ha to 100 million ha) (ALCES Group, 2013). ALCES Integrator is a STELLA based model that accepts summarized GIS and coefficient input data in Excel format and can handle a maximum number of data

inputs (20 landscape types, 10 unique seral stages, 15 footprint types, 3 human population and 3 livestock population types, 12 transport types, 12 commodity types and up to 15 input or output rates, etc…) (ALCES Group, 2013). Critical to simulating landscape dynamics, the ALCES model simulates (in either constant or stochastic mode) a full suite of natural disturbances that includes fire, insects, climate change, avalanches, and severe storms. Collectively, the simulated permutations of these land use, landscape, population and other variables allows ALCES to simultaneously track ~50 million unique values within a study area for each time step. ALCES Integrator is also able to perform Monte Carlo simulations for sensitivity analyses purposes (ALCES Group, 2013).

ALCES Mapper is the spatial modelling engine within the ALCES Toolkit and applies algorithms to spatially allocate land use and natural disturbance events. As an ArcGIS extension it can generate time-series maps (at user-defined time steps) that depict plausible future land use development based on ALCES Integrator model outputs (ALCES Group, 2013). The three primary input datasets are: spatial GIS land cover data, land use (i.e. human footprints) for the study area, and data from ALCES Integrator - specifying rates of change for land use development, land cover types, and natural disturbances (ALCES Group, 2013). ALCES Mapper divides the study area into cells of user- and data-defined resolution and applies the supplied development rates to display future spatial land use patterns (ALCES Group, 2013). Additionally, ALCES Mapper has the ability to define logical locations for footprint growth using user-defined masks that describe spatial variation in the relative likelihood of development – for instance future mine sites would be located near areas of high deposit potential and as close as possible to pre-existing infrastructure (ALCES Group, 2013). A range of inputs allow other aspects of spatial pattern to also be controlled, such as the extent to which disturbance is aggregated or dispersed.

ALCES Online is a web-based application specifically designed for "non-experts to visualize, customize, and compare land-use simulations" (Carlson et al., 2014). Simulations of land-use metrics in response to a diverse suite of indicators and drivers were completed for the full province of Alberta using ALCES Integrator and spatially displayed using ALCES Mapper. Indicators tracked by ALCES Online include attributes related water, wildlife, landscape composition, and economic performance (Carlson et al., 2014). The simulations can be extended by ALCES Online users through the creation of user-defined indicators that respond to simulated landscape dynamics, and by creating new land-use scenarios that apply strategies such as best practices and protection to portions of the landscape. ALCES Online can simulate three types of landscape scenarios: pre-disturbance (pre-industrial era), backcast (past 100 years), and forecast (future 50 years) (ALCES Group, 2014). ALCES Online is currently setup for the provinces of Alberta, British Columbia, and Manitoba at a spatial resolution of 2.5 km^2 and annual time-steps (ALCES Online, n.d), and the tool is presently being prepared for northern Ontario. Outputs from ALCES Online can be displayed in either graph or map format and can also be exported as ESRI shapefiles or CSV files for custom analysis (ALCES Online, n.d; Carlson et al., 2014).

Table 4: ALCES Toolkit simulations and output types

Simulation Type		
Disturbance	Category	
Fire	Natural Process	☑
Insect Infestation	Natural Process	☑
Climate Change	Natural Process	☑
Water Metrics	Natural Process	☑
Forestry	Human land use	☑
Energy Sector	Human land use	☑
Mining	Human land use	☑
Municipal Development	Human land use	☑
Agriculture	Human land use	☑
Output Type		
Graphical Outputs		☑
Map Outputs		☑
3D visualisations		☐

ALCES has been employed in the past for assessing water resource and land use issues in the Upper Bow River Basin (ALCES Group, 2010), the Red Deer Basin (WaterSMART, 2014), and the Wapiti River Basin. ALCES has also been used to develop an Athabasca Landscape Caribou Management Options report (Antoniuk et al., 2009), numerous peer reviewed articles concerning energy development in Alberta's oil sands region (Carlson et al., 2010; Kennett et al., 2006), and many cumulative effects studies in British Columbia and Alberta (Schneider et al., 2003; ALCES, 2010a; Wilson and Hudson, 2009). ALCES has also been applied in the Lower Athabasca Regional Plan and the Land-use Framework. ALCES is considered to be user-friendly due to its built-in graphical user interface (GUI) and its quick simulation time (minutes).

The ALCES Toolkit does have the capacity to integrate with other models. It has already been coupled to the OASIS and EwE models, as well as CSIRO model in Australia. Integration with other models is possible; however, this would be a custom application that is project-specific.

Strengths of the ALCES Toolkit include its previous application in the ARB region, and its allowance for meaningful stakeholder engagement and public participation. Significant development has occurred with the ALCES Toolkit in the last two years – addressing many of the historic limitations. The ALCES toolkit does have certain limitations including, it requires modellers with knowledge in how to use the tool and it requires further development to enhance its flexibility.

The ALCES Toolkit is good candidate model for meeting the ARB project goals, as it has extensive land use functionalities at relevant spatial and temporal scales, and it is able to link to hydrological models for a better understanding of the land use impacts on water resources. ALCES is able to simulate a

multitude of different management options and provides quantitative projections that are easy for stakeholders to understand.

2.2 LTM

The LTM (Land Transformation Model) was developed by the Human-Environment Modeling & Analysis Laboratory at Purdue University (Purdue University, 2011). Extensive web-based research found limited supporting materials. No user manual was found and it seems no workshops or training courses are provided, although an extensive video tutorial can be found on the model's webpage (HEMA, 2006). There is no cost to acquire LTM as it is an open source model. The LTM is a land-use model that is GIS and neural network based. Conceptually, the LTM has six different modules: 1) policy framework; 2) driving variables; 3) land transformation; 4) intensity of use; 5) processes and distributions; and 6) assessment endpoints (US EPA, 2000). It runs off of Microsoft Windows operating system and requires ArcGIS software. Familiarity with the programming language C++ is recommended as the model does not have a built-in GUI. It is not specified whether it can be expanded and linked to other models or external databases. The LTM model has been shown to fit observed urbanization data very well, even in different regions (e.g. USA and Albania), according to both location based and patch based metrics (Pijanowski et al., 2006).

The most commonly used time step within LTM is the yearly time step; however, it can simulate whatever time step the data can support (HEMA, 2006). The spatial scale is variable and the resolution is defined by the resolution of the input data. It supports user-defined inputs in the ascii file type at a maximum of eight land use types and accepts any type of spatial data that is compatible with GIS based raster formats (HEMA, 2006). Common types of driving variables used in the LTM include population growth, agricultural sustainability, transportation, and farmland preservation policies for the watershed (US EPA, 2000). Model simulation time is quick (matter of minutes) and outputs are given in a map format as a GIS layer. However, it is possible (through the use of ArcMap) to export data to spreadsheet programs for further custom analysis. The LTM cannot perform Monte Carlo sensitivity analyses; however, it does provide certain other statistical outputs, such as the Percent Correct Metric (PCM) and Kappa statistics in text file format (HEMA, 2006).

Table 5: LTM model simulations and output types

Simulation Type		
Disturbance	Category	
Fire	Natural Process	☐
Insect Infestation	Natural Process	☐
Climate Change	Natural Process	☐
Water Metrics	Natural Process	☑
Forestry	Human land use	☑
Energy Sector	Human land use	☐
Mining	Human land use	☐
Municipal Development	Human land use	☑
Agriculture	Human land use	☑
Output Type		
Graphical Outputs		☐
Map Outputs		☑
3D visualisations		☐

Due to the lack of GUI, the LTM is not as user friendly as certain other land use models and therefore is not as conducive to stakeholder engagement and public participation. Furthermore, the LTM has no know applications in the ARB. Its past applications have been concentrated mainly around the Great Lakes Area in the United States, to forecast urban land growth. Work by Oyebode (2007) shows how the LTM can be used to project future land use scenarios and their effects on stream flow characteristics within the Vermillion River Watershed (Oyebode, 2007), and their effects on increasing urban storm water runoff in watersheds in Indiana and Michigan (Tang et al., 2005). The LTM has also been used to make spatially explicit predictions of future urbanization in Michigan's Grand Traverse Bay Watershed (Pijanowski, 2002).

There is no documentation that shows integration of the LTM with other water quality or hydrological models. Integration may be possible; however, significant alterations are expected. The expertise of in-house technical support would be paramount for enabling integration with other models.

The LTMs strengths include the fact that it is coupled to a neural-network software package, its ability to provide stakeholders with coherent results in the form of maps, and its ability to explore impacts from various types of inputs (US EPA, 2000). Limitations include stable driver-variables, large coding programs and memory requirements, and extensive training requirements to run the model (US EPA, 2000).

The LTM may not be able to meet the overall goals of the ARB project, as it is not a best-fit tool for stakeholder engagement and it does not account for natural processes (e.g. fire, infestation) on the landscape. If integration with hydrological and water quality models is possible, LTM may be able to

relate land use change to water resource issues in the ARB and project the environmental outcomes of different management scenarios. This integration would require significant modifications to the model.

2.3 SELES

SELES (Spatially Explicit Landscape Events Simulator) is a land use model that was developed by Gowland Technologies Ltd. in collaboration with Simon Fraser University (Gowland Technologies Ltd, n.d.). An extensive literature search on this model resulted in limited supporting documentation (Fall & Fall, n.d; Riel et al., 2003; Fall, n.d; Burnett et al., 2003). There was no information on existing user manuals, sample runs, or training workshops. Likewise it was not specified anywhere if there was a cost to acquire the model.

SELES is a "raster-based, semi-Markov, whole landscape model" that uses probabilistic disturbance spreads to project future land-use (Fall & Fall, n.d.). It uses PAMPA GIS as a spatial database and FRAGSTAT as a third-party landscape statistics package (Fall & Fall, n.d.). No prior knowledge of programming language is necessary because it has a built-in GUI and it has been linked to the MPBSIM mountain pine beetle model in the past (Riel et al., 2003). The model simulation time is approximately 10 minutes for a 300 year simulation (Fall & Fall, n.d.).

SELES can function at variable time steps as well as variable spatial scales. Its smallest spatial resolution is defined by supporting data; however, each cell is assumed to be compositionally homogenous (Fall & Fall, n.d; Fall, n.d.). The model accepts a variety of raster layer formats; therefore, it can accept any type of spatial data input (e.g. hydrology data, forestry data, municipal development data, agriculture data) (Fall, n.d.). Outputs come in map format; however, you can export data to spreadsheet format as well for further analysis. The model is also capable of Monte Carlo sensitivity analysis (Fall & Fall, n.d.).

Table 6: SELES model simulations and output types

Simulation Type		
Disturbance	Category	
Fire	Natural Process	☑
Insect Infestation	Natural Process	☑
Climate Change	Natural Process	☑
Water Metrics	Natural Process	☑
Forestry	Human land use	☑
Energy Sector	Human land use	☐
Mining	Human land use	☑
Municipal Development	Human land use	☑
Agriculture	Human land use	☑
Output Type		
Graphical Outputs		☐
Map Outputs		☑
3D visualisations		☐

Although SELES has previously been employed in a study within the Canadian Boreal (Fall, n.d.) it still may not be pertinent to the ARB project. According to the developer Andrew Fall, "modelling results […] will be of use to policy makers only if […] the model [is] straightforward and simple to understand. In this respect SELES fails. It is intended for use by scientists, not policy makers." (Fall & Fall, n.d.). Furthermore, according to Fall, modelling tools useful for policy-makers must be integrated as a single tool; this is not the case for SELES which uses multiple software packages (Fall & Fall, n.d). Examples of past studies where SELES has been used include research into mountain pine beetle models (Riel et al., 2003), dynamics of boreal forest structure (Burnett et al., 2003), and impacts on grasslands from cumulative effects of timber harvesting cattle grazing and natural disturbances (Fall, n.d.).

The SELES model has limited examples of previous model integration. It has been linked to a Mountain Pine Beetle infestation model, but no examples of linkage to water quality or hydrology models exist. Integration may be possible, although extensive alterations would be necessary.

The strength of the SELES model is its ability to simulate in real-time and compute at functional scales and resolutions. Its weaknesses consist of limited supporting documentation and no previous use in the ARB.

As stated by the developers, the SELES model is not integrated as one functional tool for ease of use and therefore, is not conducive to stakeholder engagement in the ARB, which is an important project objective. Furthermore the model is not yet linked to any water quality or hydrology models and therefore significant alterations are necessary in order to meet project goals. However, SELES does consider mostly all land uses and natural processes pertinent to the ARB project.

2.4 CanWET v 4.2

CanWET (Canadian Watershed Evaluation Tool) was developed by Greenland Technologies Group and is used to simulate key watershed processes such as hydrology, contaminant loading and transport, and land scape change. The model can be used to estimate impacts of increasing population, developing land use, and changing climates (Greenland International Consulting, 2014). It is able to investigate management strategies and therefore provide decision-support for pertinent environmental management plans. CanWET is not a land use simulator but may be applicable for addressing land use questions with further development. The model was designed for decision making processes applicable to watershed management, water supply, wastewater treatment, and climate change adaptation.

CanWET functions with an open-source GIS software called MapWindow (Greenland International Consulting, 2014). CanWET has an incorporated GWLF (Generalized Watershed Loading Function) in order to simulate different pollution or nutrient loadings from different catchment areas (Greenland International Consulting, 2014). The model can also operate at a daily time step and it has built-in graphing and mapping programs for output display.

Table 7: CanWET model simulations and output types

Simulation Type		
Disturbance	Category	
Fire	Natural Process	☐
Insect Infestation	Natural Process	☐
Climate Change	Natural Process	☑
Water Metrics	Natural Process	☑
Forestry	Human land use	☑
Energy Sector	Human land use	☐
Mining	Human land use	☑
Municipal Development	Human land use	☑
Agriculture	Human land use	☑
Output Type		
Graphical Outputs		☑
Map Outputs		☑
3D visualisations		☐

CanWET applies best management practices (BMPs) by altering certain loading factors from different land-use categories. Numerous BMPs can be applied simultaneously or sequentially (Greenland International Consulting, 2014). CanWET also estimates costs for BMP implementation according to a pre-determined unit-cost. Furthermore, the model has integrated climate change scenarios, and it can incorporate loading estimates from livestock and septic contributions (Greenland International Consulting, 2014). CanWET is considered a user-friendly model as it has a built-in GUI and provides

visual outputs in real time. The following link is a helpful video tutorial on CanWET's different functionalities: https://www.youtube.com/watch?v=POYgJVgc18w

Limited documentation exists providing examples of past model integration with CanWET. A past study of Lake Simcoe and the Nottawasaga River Basins does mention linking CanWET's functionalities to a groundwater system model; however, few details are provided (Greenland International Consulting, 2006). This information implies that CanWET is capable of integration with other models; however considerable modifications may be necessary.

The main strength of the CanWET model is its user-friendliness. With its GUI, real-time simulations and visual outputs, CanWET is an optimal model for stakeholder engagement. However, CanWETs main weakness is its incorporation of the SCS curve method to estimate runoff. This method is not as accurate for modelling areas with snow and frozen ground, and therefore should be used with caution in most Canadian applications (Watts et al., 2005).

CanWET is a relatively good candidate model for meeting the ARB project goals. It was designed for water management and can therefore properly inform stakeholders of water resource issues. CanWET is also able to assess different best management practice options and project outcomes into the future. However, in terms of understanding and projecting land use change in the ARB, CanWET is only able to simulate a fraction of the land use components and does not consider all natural disturbances either. Furthermore, CanWET only provides quantitative outputs at the watershed scale and not at a flexible or user-defined resolution.

2.5 NetLogo (GeoSimulation)

NetLogo is a free, open source, agent-based modelling environment developed by Uri Wilensky in 1999 (NetLogo, 2014). Netlogo is designed to model complex systems which evolve over time; therefore, it is of particular use when modelling landscape change. This modelling platform is comprised of multiple agents that all operate independently under distinct sets of rules, allowing the user to investigate relationships between the fine-scale development of individual agents and the broad-scale patterns that unfold from agent-interactions (NetLogo, 2014).

An example of NetLogo's use, involves its application by Alberta Innovates - Technology Future (AITF) in the South Athabasca Oil Sands Regional Strategic Assessment (SAOSRSA) to simulate the cumulative effects of land disturbance on various indicators. Detailed documentation is lacking in order to verify the results of this assessment; however, part of the work conducted uses NetLogo as a modelling platform to assess the effects of natural disturbance and human footprint on biodiversity under three energy production scenarios (low, medium, and high) and a forest harvest scenario. Future energy development was simulated through the random generation of energy facilities based on proximity to existing energy infrastructure and location of bitumen deposits by the Department of Energy, while

future forestry development was modelled through consultation with forestry professionals (ESRD, 2014). This model functions on an annual time step (projecting 50 years into the future) and model outputs can be tailored to specific locations of interest. Model outputs include mammal species occurrence, bird species relative abundance, caribou population rate of increase, various ecosystem metrics, and Biodiversity Intactness Index. Outputs from the SAOSRSA model are also used as input to hydrological and water quality models, although there is currently limited information available on how exactly this was done.

Table 8: NetLogo-based SAOSRSA model simulations and output types

Simulation Type		
Disturbance	Category	
Fire	Natural Process	☑
Insect Infestation	Natural Process	☑
Climate Change	Natural Process	☑
Water Metrics	Natural Process	☑
Forestry	Human land use	☑
Energy Sector	Human land use	☑
Mining	Human land use	☑
Municipal Development	Human land use	☑
Agriculture	Human land use	☑
Output Type		
Graphical Outputs		☑
Map Outputs		☑
3D visualisations		☐

Agent-based models, like NetLogo, can have applications in the field of land use and land cover change (LUCC) because they can incorporate the impacts of human decisions on land use, in a mechanistic and spatially explicit way, while also accounting for socio-economic influences (Matthews et al., 2007). Examples of past agent-based models that have been applied to the field of LUCC, include lands pattern models such as the SLUDGE model which explores patterns of urban development and land use, or the SIMPOP model which studies the evolution of rural settlement patterns (Matthews et al., 2007). Other models can study deforestation patterns (LUCIM model), or agriculture expansion patterns (Matthews et al., 2007). LUCC models using the NetLogo platform include, a farmland expansion model developed for rural Germany (Valbuena et al., 2010), and a land use development model assessing the influences of risk-regarding agent behaviours (Hosseinali et al., 2012). NetLogo is also applicable to a broad range of disciplines from biology and physics to social sciences and urban planning (NetLogo, 2014). NetLogo is a user-friendly platform for participatory modelling, as it has been designed for and used in classroom environments for education purposes (NetLogo, 2014).

NetLogo based models are known to integrate well with Java and R software to increase speeds and improve functionalities. NetLogo models can also integrate with GIS programs. Specifically, the SAOSRSA model has been linked to Mike11, Mike-SHE, and FeFlow for surface and ground water quality and quantity modelling (Alberta ESRD, 2014).

Limitations inherent to the SAOSRSA model include simplifications and assumptions about underlying ecological rates of change. Furthermore, vegetation type was not changed dynamically with time; therefore, this model does not take into consideration changes in plant community structure after disturbances or within forest successions. A more detailed assessment of this specific SAOSRSA modelling tool is required and it is expected that this will be available in the near term.

The NetLogo-based SAOSRSA model is a good candidate model for meeting the ARB project goals. Model outputs are linked to hydrological and water quality models to provide results on how land use changes impact water resources. It is also considered a good stakeholder engagement tool and provides visual outputs that are easy for the public to understand. The SAOSRSA model is also able to simulate different projection scenarios and adaptation options. However, as specified above, vegetation dynamics are not modelled as accurately as possible and certain limitations to the model exist.

2.6 TELSA

Designed by ESSA Technologies Ltd., The Tool for Exploratory Landscape Scenario Analyses (TELSA) is a GIS based landscape model that is primarily used for simulating vegetation dynamics. Supporting documentation is available for this model and workshop training courses and guidance from the developers are offered at a cost (ESSA Technologies Ltd., 2014). TELSA is an open source model that is freely available. It requires a 32-bit Windows operating system as well as ArcGIS and VDDT software (ESSA Technologies Ltd., 2008). No prior knowledge of the ArcGIS scripting language is necessary as TELSA has a graphical user interface. TELSA cannot simulate multiple processes apart from vegetation dynamics (i.e. natural processes in other domains). It can address questions concerning how vegetation dynamics react to natural and human disturbances (fire, pest outbreak, climate change, logging) and the effects that different management scenarios can have on these dynamics (ESSA Technologies Ltd., 2008).

In order to simulate forest succession dynamics, TELSA models large time-steps on the order of decades to centuries (ESSA Technologies Ltd., 2008). It is applied at the regional landscape scale at a user-defined resolution. The model also supports user-defined inputs in the GIS vector format; therefore it can accept mostly any type of spatial data. Simulation time is quick (matter of minutes) and outputs can be displayed in graphical or map format (ESSA Technologies Ltd., 2008). Monte Carlo

simulations can be run to identify the range of possible outcomes to specific forest management scenarios (ESSA Technologies Ltd., 2008).

Table 9: TELSA model simulations and output types

Simulation Type		
Disturbance	Category	
Fire	Natural Process	☑
Insect Infestation	Natural Process	☑
Climate Change	Natural Process	☑
Water Metrics	Natural Process	☐
Forestry	Human land use	☑
Energy Sector	Human land use	☐
Mining	Human land use	☐
Municipal Development	Human land use	☐
Agriculture	Human land use	☐
Output Type		
Graphical Outputs		☑
Map Outputs		☑
3D visualisations		☐

TELSA has a GUI and was designed so that (once proper parameters are input) non-experts can use it and comprehend model outputs (ESSA Technologies Ltd., 2008). TELSA has been previously applied in many regions of the Pacific Northwest to address research questions such as the effects of management practices and natural disturbance on habitat patterns in BC forests (Klenner et al., 2000) and the cumulative effects of management and disturbance on regional landscapes in Northeast Oregon (Hemstrom et al., 2007). This model is relevant to water management, as it can quantify and predict changes in vegetated landscapes in the ARB, which then (if linked to a hydrological model) can project changes in water resources. TELSA is an ArcGIS toolbox model; therefore, it can integrate with other spatially explicit models via the GIS platform.

The main advantage of the TELSA model is that it accounts for natural disturbances and projects how these natural processes will interact with anthropogenic management plans. One significant weakness of TELSA is that it only provides a modelling framework, requiring an interdisciplinary team of experts to build each model (Lee et al., 2003).

The TELSA model is not a suitable candidate for meeting ARB project objectives. The model is not integrated with any water resources models (although this may be possible with alterations via the GIS platform) and it does not account for many other land uses besides forestry. Furthermore, it does not model at a small enough time-step. It therefore would not provide any accurate projections of land

use change over time in the ARB. It does however have the ability to simulate different management options and it is considered stakeholder friendly (after parameters are input by experts).

2.7 What if?

What if? is a spatially explicit GIS-based planning support system, which tracks land use, population, housing and employment projections (Whatif? Inc.,2014a). An accompanying user manual and tutorial exist for this model; however, no workshops are available at this time and support from the developer is limited (Whatif?Inc., 2014b). The What if? software is available free of charge without any model support (Whatif? Inc.,2014a). It uses the Windows operating system and requires ArcGIS third party software. It is not directly linked with any environmental databases; however, it does utilize information from external databases such as the United States National Landcover database (Klosterman, 2011).

What if? simulations can be modelled on a yearly or longer time-step and at an urban to regional spatial scale. The smallest resolution for model simulations is defined by the resolution of the input data. What if? accepts any type of GIS spatial data that has been transformed into UNION file format (Klosterman, 2011). The model accepts a maximum of 30 landuse types and 20 suitability factors (Klosterman, 2011). Simulations run in a matter of minutes and outputs are displayed in map format or alternatively can be exported into spreadsheet programs via ArcGIS (Klosterman, 2011). As far as our research shows, no statistical analyses or Monte Carlo simulations are possible within this model.

Table 10: What if? model simulations and output types

Simulation Type		
Disturbance	Category	
Fire	Natural Process	☐
Insect Infestation	Natural Process	☐
Climate Change	Natural Process	☐
Water Metrics	Natural Process	☐
Forestry	Human land use	☑
Energy Sector	Human land use	☑
Mining	Human land use	☑
Municipal Development	Human land use	☑
Agriculture	Human land use	☑
Output Type		
Graphical Outputs		☐
Map Outputs		☑
3D visualisations		☐

What if? is considered a user-friendly model, as no programming language is required for its use, due to its functional GUI. This model is specifically focussed on urbanisation and can be used to create sustainable urban growth management plans (Asgary et al., 2007) or even assess projected health of watersheds based on growth of impervious surfaces (McClintock & Cutforth, 2003). What if? has not been previously used in the ARB. What if? is a GIS-based modelling tool; therefore, it is possible to link with other models via the GIS platform.

The main strength of the What if? model lies in its flexibility; it is possible to use this model in various regions at various resolutions. The primary limitation inherent in this model is that there are few endogenous processes; the user assigns the rules and the model simply grows out and displays those user-defined inputs (Klosterman, 2011).

The What if? model does not account for any natural processes on the landscape and models at a large time-step; therefore, it is not the best suited model for fulfilling ARB objectives, as it would not accurately project future changes on the landscape. It is also not currently integrated with any water resource models; however, this would be possible via the GIS platform.

Model Ranking

A model ranking scheme was developed to compare the eight selected land use models to various evaluation criteria. Criteria were defined based on the extent to which the model was publically available, the amount of required technical support, the degree of computing requirements, the different model scales (both spatial and temporal), the potential to link to other models and the specific components that are able to be simulated. Further details on the numerical ranking of each of the criteria are described below:

1. Public accessibility – Is the model publicly accessible and affordable? Rank [1-3]; 1 for publicly available and an annual subscription fee, 2 for publicly available with modest fees, and 3 for publicly available with no subscription fee.
2. Model Support –documentation (e.g. manuals, sample runs, workshops). Rank [0-2]; 0 for very limited documentation (web-pages only), 1 for moderate supporting materials (user manual and sample runs only), 2 for extensive documentation and materials (peer-reviewed references).
3. Degree of in house technical support [Rank 0-2]; 0 for high degree of technical support required, 1 for average support required, 2 for limited support required.
4. Computing – based on the following questions: 1) Does model allow user-defined inputs? 2) Can model project outcomes for multiple variables? 3) Can the model be applied to locations other than for which it was developed? 4) Is the run-time fast (matter of minutes)? Rank [0-4]; one point for each.
5. Model Scales – based on spatial and temporal scale. Rank [0-3]; one point for a monthly time step or smaller, 0 for time steps greater than monthly; one point for a flexible or regional

spatial scale, 0 for smaller spatial scales; and one point for a varied cell (pixel) sizes and ability to scale appropriately to the input data, 0 for non-scalable.

6. Linkage Potential – Can the model link to other models or external environmental databases? Rank [0-2]; 0 for no, 1 for linking to other models; 2 for linking to other models and environmental databases.
7. Modelling Components – Can the model simulate the following natural processes and human land uses: fire, insect infestations, climate change, water metrics, forestry, energy sector, mining, municipal development, and agriculture through time. Are forecasts and back casts available? Rank [0-10]; one point for each.
8. Stakeholder Engagement – based on the following questions: 1) Does the model have a built-in GUI? [0 for no, 1 for yes] 2) Does the model present results in a visual fashion? [0 for no, 1 for graphical results, 2 for map results, and 3 for 3D or animated results] 3) Does the model encourage active stakeholder engagement? [0 for no, 1 for yes] 4) does the model give results in real time? [0 for no, 1 for yes]
9. Previous use in the ARB – Has the model been previously used in the ARB? Rank [0-1]; 0 for no, 1 for yes.

Figures 11 through 17 in the following section provides a breakdown of how each model scored.

Table 11: Score breakdown for ALCES Toolkit

ALCES				
Criteria	Sub-topic	Sub-criteria	Points	
1. Public Accessibility		Publically available on an annual subscription	1	☐
		Publically available with modest fees	2	☐
		Publically available with no fees	3	☑
2. Model Support	Documentation	limited documentation	0	☐
		moderate documentation	1	☐
		extensive documentation	2	☑
	Technical Support	High degree of in-house technical support required	0	☐
		Average in-house tech support required	1	☑
		limited support required	2	☐
3. Computing		Does model allow user-defined inputs?	1	☑
		Can model project outcomes for multiple variables?	1	☑
		Can model be applied to locations other than for which it was developed?	1	☑
		Is the run-time fast?	1	☑
4. Model Scales	Time step	Monthly or smaller?	1	☑
	Spatial Scale	Flexible or regional scale?	1	☑
	Resolution	Varied and flexible?	1	☑
5. Linkage Potential		Can model link to other models?	1	☑
		Can model link to environmental databases?	1	☐
6. Modelling Components	Natural processes	Fire?	1	☑
		Insect Infestations?	1	☑
		Climate Change?	1	☑
		Water Metrics?	1	☑
	Human land uses	Forestry?	1	☑
		Energy Sector?	1	☑
		Mining?	1	☑
		Municipal Development?	1	☑
		Agriculture?	1	☑
	Forecast & Backcast	Are forecasts and backcasts available?	1	☑
7. Stakeholder Engagement		Does the model have a built-in GUI?	1	☑
		Provision of graphical results?	1	☑
		Provision of map results?	1	☑
		Provisoin of 3D simulations?	1	☐
		Does the model encourage stakeholder engagement?	1	☑
		Does the model give results in real-time?	1	☑
8. Previous Use in ARB		Has the model been previously used in the ARB?	1	☑
		Total Points	30	

Table 12: Scoring breakdown for LTM model

LTM				
Criteria	Sub-topic	Sub-criteria	Points	
1. Public Accessibility		Publically available on an annual subscription	1	☐
		Publically available with modest fees	2	☐
		Publically available with no fees	3	☑
2. Model Support	Documentation	limited documentation	0	☑
		moderate documentation	1	☐
		extensive documentation	2	☐
	Technical Support	High degree of in-house technical support required	0	☑
		Average in-house tech support required	1	☐
		limited support required	2	☐
3. Computing		Does model allow user-defined inputs?	1	☑
		Can model project outcomes for multiple variables?	1	☑
		Can model be applied to locations other than for which it was developed?	1	☑
		Is the run-time fast?	1	☑
4. Model Scales	Time step	Monthly or smaller?	1	☑
	Spatial Scale	Flexible or regional scale?	1	☑
	Resolution	Varied and flexible?	1	☑
5. Linkage Potential		Can model link to other models?	1	☐
		Can model link to environmental databases?	1	☐
6. Modelling Components	Natural processes	Fire?	1	☐
		Insect Infestations?	1	☐
		Climate Change?	1	☐
		Water Metrics?	1	☑
	Human land uses	Forestry?	1	☑
		Energy Sector?	1	☐
		Mining?	1	☐
		Municipal Development?	1	☑
		Agriculture?	1	☑
	Forecast & Backcast	Are forecasts and backcasts available?	1	☑
7. Stakeholder Engagement		Does the model have a built-in GUI?	1	☐
		Provision of graphical results?	1	☐
		Provision of map results?	1	☑
		Provisoin of 3D simulations?	1	☐
		Does the model encourage stakeholder engagement?	1	☐
		Does the model give results in real-time?	1	☑
8. Previous Use in ARB		Has the model been previously used in the ARB?	1	☐
		Total Points	17	

Table 13: Scoring breakdown for SELES model

SELES				
Criteria	Sub-topic	Sub-criteria	Points	
1. Public Accessibility		Publically available on an annual subscription fee	1	☐
		Publically available with modest fees	2	☐
		Publically available with no fees	3	☑
2. Model Support	Documentation	limited documentation	0	☑
		moderate documentation	1	☐
		extensive documentation	2	☐
	Technical Support	High degree of in-house technical support required	0	☐
		Average in-house tech support required	1	☑
		limited support required	2	☐
3. Computing		Does model allow user-defined inputs?	1	☑
		Can model project outcomes for multiple variables?	1	☑
		Can model be applied to locations other than for which it was developed?	1	☑
		Is the run-time fast?	1	☑
4. Model Scales	Time step	Monthly or smaller?	1	☑
	Spatial Scale	Flexible or regional scale?	1	☑
	Resolution	Varied and flexible?	1	☑
5. Linkage Potential		Can model link to other models?	1	☑
		Can model link to environmental databases?	1	☐
6. Modelling Components	Natural processes	Fire?	1	☑
		Insect Infestations?	1	☑
		Climate Change?	1	☑
		Water Metrics?	1	☑
	Human land uses	Forestry?	1	☑
		Energy Sector?	1	☐
		Mining?	1	☑
		Municipal Development?	1	☑
		Agriculture?	1	☑
	Forecast & Backcast	Are forecasts and backcasts available?	1	☑
7. Stakeholder Engagement		Does the model have a built-in GUI?	1	☑
		Provision of graphical results?	1	☐
		Provision of map results?	1	☑
		Provisoin of 3D simulations?	1	☐
		Does the model encourage stakeholder engagement?	1	☐
		Does the model give results in real-time?	1	☑
8. Previous Use in ARB		Has the model been previously used in the ARB?	1	☐
		Total Points	24	

Table 14: Scoring breakdown for CanWET model

CanWET				
Criteria	Sub-topic	Sub-criteria	Points	
1. Public Accessibility		Publically available on an annual subscription fee	1	☐
		Publically available with modest fees	2	☑
		Publically available with no fees	3	☐
2. Model Support	Documentation	limited documentation	0	☐
		moderate documentation	1	☐
		extensive documentation	2	☑
	Technical Support	High degree of in-house technical support required	0	☐
		Average in-house tech support required	1	☐
		limited support required	2	☑
3. Computing		Does model allow user-defined inputs?	1	☐
		Can model project outcomes for multiple variables?	1	☑
		Can model be applied to locations other than for which it was developed?	1	☑
		Is the run-time fast?	1	☑
4. Model Scales	Time step	Monthly or smaller?	1	☑
	Spatial Scale	Flexible or regional scale?	1	☑
	Resolution	Varied and flexible?	1	☐
5. Linkage Potential		Can model link to other models?	1	☐
		Can model link to environmental databases?	1	☑
6. Modelling Components	Natural processes	Fire?	1	☐
		Insect Infestations?	1	☐
		Climate Change?	1	☑
		Water Metrics?	1	☑
	Human land uses	Forestry?	1	☑
		Energy Sector?	1	☐
		Mining?	1	☑
		Municipal Development?	1	☑
		Agriculture?	1	☑
	Forecast & Backcast	Are forecasts and backcasts available?	1	☑
7. Stakeholder Engagement		Does the model have a built-in GUI?	1	☑
		Provision of graphical results?	1	☑
		Provision of map results?	1	☑
		Provisoin of 3D simulations?	1	☐
		Does the model encourage stakeholder engagement?	1	☑
		Does the model give results in real-time?	1	☑
8. Previous Use in ARB		Has the model been previously used in the ARB?	1	☐
		Total Points	24	

Table 15: Scoring breakdown for the NetLogo (Geosimulation) SAOSRSA model

NetLogo (Geosimulation)				
Criteria	Sub-topic	Sub-criteria	Points	
1. Public Accessibility		Publically available on an annual subscription fee	1	☐
		Publically available with modest fees	2	☐
		Publically available with no fees	3	☑
2. Model Support	Documentation	limited documentation	0	☑
		moderate documentation	1	☐
		extensive documentation	2	☐
	Technical Support	High degree of in-house technical support required	0	☐
		Average in-house tech support required	1	☑
		limited support required	2	☐
3. Computing		Does model allow user-defined inputs?	1	☑
		Can model project outcomes for multiple variables?	1	☑
		Can model be applied to locations other than for which it was developed?	1	☑
		Is the run-time fast?	1	☑
4. Model Scales	Time step	Monthly or smaller?	1	☐
	Spatial Scale	Flexible or regional scale?	1	☑
	Resolution	Varied and flexible?	1	☑
5. Linkage Potential		Can model link to other models?	1	☑
		Can model link to environmental databases?	1	☐
6. Modelling Components	Natural processes	Fire?	1	☑
		Insect Infestations?	1	☑
		Climate Change?	1	☑
		Water Metrics?	1	☑
	Human land uses	Forestry?	1	☑
		Energy Sector?	1	☑
		Mining?	1	☑
		Municipal Development?	1	☑
		Agriculture?	1	☑
	Forecast & Backcast	Are forecasts and backcasts available?	1	☑
7. Stakeholder Engagement		Does the model have a built-in GUI?	1	☑
		Provision of graphical results?	1	☑
		Provision of map results?	1	☑
		Provisoin of 3D simulations?	1	☑
		Does the model encourage stakeholder engagement?	1	☑
		Does the model give results in real-time?	1	☑
8. Previous Use in ARB		Has the model been previously used in the ARB?	1	☑
		Total Points	28	

Table 16: Scoring breakdown for TELSA model

TELSA				
Criteria	Sub-topic	Sub-criteria	Points	
1. Public Accessibility		Publically available on an annual subscription fee	1	☐
		Publically available with modest fees	2	☐
		Publically available with no fees	3	☑
2. Model Support	Documentation	limited documentation	0	☐
		moderate documentation	1	☐
		extensive documentation	2	☑
	Technical Support	High degree of in-house technical support required	0	☐
		Average in-house tech support required	1	☑
		limited support required	2	☐
3. Computing		Does model allow user-defined inputs?	1	☑
		Can model project outcomes for multiple variables?	1	☑
		Can model be applied to locations other than for which it was developed?	1	☑
		Is the run-time fast?	1	☑
4. Model Scales	Time step	Monthly or smaller?	1	☐
	Spatial Scale	Flexible or regional scale?	1	☑
	Resolution	Varied and flexible?	1	☑
5. Linkage Potential		Can model link to other models?	1	☑
		Can model link to environmental databases?	1	☐
6. Modelling Components	Natural processes	Fire?	1	☑
		Insect Infestations?	1	☑
		Climate Change?	1	☑
		Water Metrics?	1	☐
	Human land uses	Forestry?	1	☑
		Energy Sector?	1	☐
		Mining?	1	☐
		Municipal Development?	1	☐
		Agriculture?	1	☐
	Forecast & Backcast	Are forecasts and backcasts available?	1	☑
7. Stakeholder Engagement		Does the model have a built-in GUI?	1	☑
		Provision of graphical results?	1	☑
		Provision of map results?	1	☑
		Provisoin of 3D simulations?	1	☐
		Does the model encourage stakeholder engagement?	1	☑
		Does the model give results in real-time?	1	☑
8. Previous Use in ARB		Has the model been previously used in the ARB?	1	☐
		Total Points	23	

Table 17: Scoring breakdown for What if? Model

What if?				
Criteria	Sub-topic	Sub-criteria	Points	
1. Public Accessibility		Publically available on an annual subscription fee	1	☐
		Publically available with modest fees	2	☐
		Publically available with no fees	3	☑
2. Model Support	Documentation	limited documentation	0	☐
		moderate documentation	1	☑
		extensive documentation	2	☐
	Technical Support	High degree of in-house technical support required	0	☐
		Average in-house tech support required	1	☑
		limited support required	2	☐
3. Computing		Does model allow user-defined inputs?	1	☑
		Can model project outcomes for multiple variables?	1	☑
		Can model be applied to locations other than for which it was developed?	1	☑
		Is the run-time fast?	1	☑
4. Model Scales	Time step	Monthly or smaller?	1	☐
	Spatial Scale	Flexible or regional scale?	1	☑
	Resolution	Varied and flexible?	1	☑
5. Linkage Potential		Can model link to other models?	1	☐
		Can model link to environmental databases?	1	☐
6. Modelling Components	Natural processes	Fire?	1	☐
		Insect Infestations?	1	☐
		Climate Change?	1	☐
		Water Metrics?	1	☐
	Human land uses	Forestry?	1	☑
		Energy Sector?	1	☑
		Mining?	1	☑
		Municipal Development?	1	☑
		Agriculture?	1	☑
	Forecast & Backcast	Are forecasts and backcasts available?	1	☑
7. Stakeholder Engagement		Does the model have a built-in GUI?	1	☑
		Provision of graphical results?	1	☐
		Provision of map results?	1	☑
		Provisoin of 3D simulations?	1	☐
		Does the model encourage stakeholder engagement?	1	☑
		Does the model give results in real-time?	1	☑
8. Previous Use in ARB		Has the model been previously used in the ARB?	1	☐
		Total Points	21	

Table 18 provides the total score and the sum of all ranked criteria out of a maximum of 33 for each of the categories and associated points for each model.

Table 18: Land use model ranking

	ALCES Toolkit	LTM	SELES	CanWet	NetLogo (Geosimulation) SAOSRSA model	TELSA	What if?
Public Accessibility (Max = 3)	3	3	3	2	3	3	3
Model Support (Max = 4)	3	0	1	4	1	3	2
Computing (Max = 4)	4	4	4	3	4	4	4
Model Scales (Max = 3)	3	3	3	2	2	2	2
Linkage Potential (Max = 2)	1	0	1	1	1	1	0
Modelling Components (Max = 10)	10	5	9	7	10	5	6
Stakeholder Engagement (Max = 6)	5	2	3	5	6	5	4
Previous Use in ARB (Max = 1)	1	0	0	0	1	0	0
Total (Max = 33)	**30**	**17**	**24**	**24**	**28**	**23**	**21**

The relative order of ranked models from highest to lowest is ALCES > SAOSRSA model > SELES = CanWET > TELSA > What if? > LTM. This model review suggests that the ALCES Toolkit is the most applicable for the ARB Project. This is primarily based on model functionality and its applicability to stakeholder engagement. However, given that NetLogo–based SAOSRSA model also ranked high, further research is necessary to gain information and to determine how the highest ranking models can be applied either in parallel or collaboratively to help achieve ARB project goals.

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3. Draft River System Model Review

River System models can be used to assess implications of a range of different water resource operation scenarios, promote communication and compromise among conflicting interests, and support decision making processes for sustainable water resource management.

There are multiple river system models available for use that can help the user achieve sustainable watershed management. This project has focused on a subset of models that have been widely applied in the North American context. The subset of models includes:

- REGUSE (Basin Regulation and Water Use Model)
- OASIS (Options Analysis in Irrigation Systems)
- WRMM (Water Resource Management Model)
- HCMS (Hydro Configuration Modelling System)
- WUAM (Water Use Analysis Model)
- WEAP (Water Evaluation and Planning System)

A good river system model should be able to properly simulate the effects of different operation or management scenarios on multi-sectoral water use in a multi reservoir/channel river system (Dinar et al., 2007). These models should be mathematically based and data driven through the input of direct hydrological information (Dinar et al., 2007). Furthermore, incorporation of non-hydrology data such as water pricing, water rationing, hydro-power generation, ecosystem integrity metrics, instream flow requirements etc. is desirable. A user-friendly model is also necessary as it allows stakeholders to directly interact in model simulation sessions and henceforth become engaged in the watershed management process. This model review attempts to isolate a “best-practice” river system model that is applicable to the ARB region while satisfying the objectives of the ARB project. When choosing a model it is important to remember that the Athabasca River is an unregulated system, which means that its flow is not altered by any dams or reservoirs (RAMP, n.d.).

The remainder of this report describes the river system models currently under consideration, ranks them according to their application to the ARB, and highlights certain models for further consideration. Table 5 provides a summary of the river system model review. Additional tables and details from the river sytem model review are available in Appendix C of this report.

Table 19: River System Model Summary

*Dash indicates 'no information available'

MODEL NAME	REGUSE	OASIS	WRMM	HCMS	WUAM	WEAP
MODEL TYPE	Network flow approach using out-of-kilter optimization algorithm for linear programming	Arc and Node model using linear programmin g solver	Arc and Node model using linear programmi ng solver	Semi-distributed model using IBM linear programmi ng optimizatio n	River Node model – optimization algorithm not specified	Node and link system with linear programming solver
LICENSE COST	-	No fee with Hydrologic's involvement OR fee without invovlement	None	-	None	Yes
MODEL SUPPORT	-	Yes	Limited	-	Limited	Yes
COMPUTING						
Equipment	PC	Microsoft, XA solver	Microsoft, OKA or Lindo systems	-	PC	Microsoft Windows
GUI	-	Yes	No	-	No	Yes
Publicly available	-	Yes	Yes	-	Yes	No
Link Environ. Databases	-	Yes	Yes	-	-	Yes
Model simulation time	-	minutes	minutes	-	-	minutes
Multiple time step optimization?	-	Yes	No in general but a version exists	No	-	-
MODEL SCALE						
Time Step	D/M	variable	W	-	M	Monthly
Planning Scale	-	Flexible	Flexible	-	Flexible	River basins
Integrated with others?	-	possible	possible	-	No	Yes
RIVER SYSTEM						

COMPONENTS						
Non-hydrology data?	-	Yes	No	-	Yes	Yes
Allocation priorities?	Yes	Yes	Yes	-	Yes	Yes
Channel routing?	Yes	Yes	Yes	-	-	-
Previously used in ARB?	-	No	No	No	No	No
STAKEHOLDER ENGAGEMENT						
Facilitates stakeholder engagement?	No	Yes	No	-	-	Yes

3.1 REGUSE

The REGUSE model (or Basin Regulation and Water Use Model) was developed by the Ecosystems Modelling and Analysis Section in the Economics and Conservation Branch of Environment Canada (Riecken, 1995). A user manual exists although access to documentation is limited; therefore, detailed information regarding the model is also lacking. It is assumed that support and training sessions or workshops are not available as there is limited information concerning this model. The cost to acquire it is also unknown.

The REGUSE model uses a network-flow optimization algorithm for flow-regulation and planning multi-user, multi-reservoir/channel networks (Environment Canada, 2010). The model's main functionalities include fast real-time simulations (Riecken, 1995), and inclusion of channel routing in the solution process (Environment Canada, 2010). The model uses an "out-of-kilter" optimization algorithm and penalty coefficients for allocation priorities (Ouellet, 1995). The REGUSE model simulates daily and monthly time steps (Environment Canada, 2010). This model also supports user-defined inputs (Ouellet, 1995).

Although stakeholders cannot directly interact in the model building and validation processes, model outputs still support stakeholder contributions and decision-making (Ouellet, 1995). For example, past application of the REGUSE model in the St-Croix river basin facilitated the engagement of stakeholders in water management discussions and allowed for different water-use scenarios to be simulated and discussed. Model results from these scenarios supported conflict-resolution, compromise, and subsequent policy recommendations (Ouellet, 1995). The REGUSE model has not yet been applied to the ARB or the Boreal region.

3.2 OASIS

The OASIS (Options Analysis in Irrigation Systems) model was developed by Hydrologics Inc. in 2009 (Hydrologics, 2014). The model is accompanied by a detailed user manual as well as tutorials, training

courses and extensive support from the Hydrologics team (SSRB Project, 2012). There is no cost for acquiring the OASIS model, and the solver comes with a proprietary software license. Furthermore Hydrologics charges for services in building the OASIS model for project specific functions (SSRB Project, 2012).

OASIS is an arc and node type model which simulates the routing of water through a multi-user water resource system (Hydrologics, 2014). The model runs off PC-based Microsoft Windows and utilizes VEDIT, XA, MetaDraw, and True DBGrid third party softwares (Hydrologics, 2009). OASIS uses an operations control language (OCL), which allows the user to model a system by simply defining a set of operating goals and constraints (Hydrologics, 2009). This means that the source code never has to be altered. OASIS has a built-in Windows-based graphical user interface (GUI), making the model user-friendly for stakeholder engagement. Users can create their water system schematic of nodes and arcs and define their operating goals, constraints, and variables such as priority levels, using this GUI (Hydrologics, 2009). User defined inputs can be entered into the model this way as well. The linear programming solver (XA) can optimize multiple time steps at once (MTO mode), which also enables channel routing to be properly applied (SSRB Project, 2012).

OASIS typically functions at hourly to monthly time steps (or whatever the data can support), and can be applied to variable sized basins from small and simple to large and complex (Hydrologics, 2014). The model runs quickly (matter of minutes) and provides direct graphical outputs using intrinsic plot-maker tools. Some key model outputs include water balances, flows, shortages, evaporation, and reservoir elevations. OASIS also gives a time-series outputs that are meant for post-processing purposes (Hydrologic, 2009). All outputs can be used in user-defined Performance Measures that are calculated in plot-maker tools.

One of the main strength of OASIS is its flexibility. The model was designed to be very flexible, allowing you to build completely new models or modify existing ones (Hydrologics, 2009). One of the biggest advantages of OASIS is its use of the OCL language allows you to write new operating rules with user-defined forms and parameter values (Hydrologics, 2009). This feature allows for simulation of different operating rules and implementation of alternative management scenarios.
The fast processing time, coherent outputs and built-in GUI, allow for direct stakeholder engagement in the water management process. In fact, the OASIS model originated from a stakeholder engagement process which used an OASIS-predecessor as an integral tool for stakeholder participation (Sheer et al., 1989). A past example of OASIS' real world application extends to its use in the Bow River Project (BRP), the South Saskatchewan Adaptation Project, and the SSRB Water Project (Kelly, 2012; University of Lethbridge, 2014; WaterSMART, 2014; WaterSMART, in prep). OASIS has also been applied to investigate how climate induced changes in snowmelt and runoff timing will affect water storage and operation of the New York City Water Supply System (NYCWSS) (Matonse et al., 2011). These projects and others demonstrate that OASIS is a good example of a computer-aided negotiation tool (Rivera & Sheer, 2013).

3.3 WRMM

The Water Resource Management Model (WRMM) was developed by Alberta Environment and Sustainable Resource Development (ESRD). Training support from ESRD is limited, yet this model is widely used in Alberta; therefore, support may be available from other means. A user manual does exist, yet is accessible only upon model acquisition. The WRMM is a free program with open source code. However, an updated version of the WRMM, coined WRM-DSS is currently in development (in the Beta testing stage) and will require a license for the solver software (SSRB Project, 2012; Unitech Solutions, 2013)).

The WRMM is a river-node model aiming to facilitate long-term basin planning and short-term operational planning for water use within a river basin (SSRB Project, 2012). The WRMM runs off a Windows based PC and uses Out-Of-Kilter optimization algorithms for linear programming, while the WRM-DSS uses Lindo Systems mixed integer barrier solver version 6 (SSRB Project, 2012). A windows-based GUI is being developed for the WRM-DSS. The model uses C++ programming language but prior knowledge of this code is not necessary as data is entered using specific syntax rules in text files (SSRB Project, 2012The WRMM is a powerful model as its simulation time is fast (minutes) and it stores output files in a database to link to other models sequentially.

The WRMM was developed for weekly time steps; however, simulating other time steps is possible up to a maximum of 52 steps per cycle. There is no MTO mode available in the current version of WRMM; therefore, it cannot solve multiple time steps simultaneously, only single time optimization (STO) is possible. A newer version of WRMM is said to have MTO, this has not been confirmed. Muskingum channel routing is possible; however, should be used with caution since it uses static coefficients even though they change as a function of flow (SSRB Project, 2012). The fundamental spatial unit of the model is the river basin and it is flexible with basin configuration. Hydrology inputs are entered into the model in text files format. The WRMM model is limited to approximately 500-800 components, while the WRM-DSS version is considered to be unlimited. Model outputs are linked to MS Access or Excel for graphical display.

The development of the GUI in the WRM-DSS version is key for proper stakeholder engagement in watershed management projects. But until that is developed, the WRMM is not user-friendly for meaningful and direct stakeholder engagement. This model has been shown to be effective in the province of Alberta having been used in the South Saskatchewan River Basin (SSRB) project. Phase 2 modelling results of the project show scenarios in which available water is allocated to various demands, including environmental requirements, and water storages are managed to minimize shortages during low flow periods (SSRB Water Management Plan Phase 2, 2003). WRMM has also been used in the Malahayu reservoir system in Indonesia to assess the potential for increased reservoir yield by implementing a more efficient reservoir policy (Ilich et al., 2000).

3.4 HCMS

The Hydro-Configuration Modelling System (HCMS) was developed by Environment Canada. Supporting documentation for this model is lacking; therefore, detailed information concerning the model's basis is

limited. Nevertheless, it is known that this model solves time steps individually and uses the IBM linear programming optimization routine DOSPB of the package SL-MATH (Environment Canada, 2010). It has been historically employed on the Ottawa River to study potential hydroelectric energy production and flood control from a series of alternate operating policies (Parker & Farley, 1980). The results of the HCMS modelling scenarios supported recommendations that were later adopted by the federal-provincial committee (Parker & Farley, 1980). To date there is no information outlining the use of HCMS in the ARB.

3.5 WUAM

The Water Use Analysis Model (WUAM) was developed by Environment Canada to simulate the effects of multi-sectoral water use on a single river basin (Beckers et al., 2009). Although there are no workshops or training courses available for this model, sample runs exist as hypothetical examples in the model's user manual (Kassem, 1992). There are no associated costs with acquiring the model and contact with the developer is necessary for acquiring the source code.

In WUAM, a river system is represented as a dendritic network of nodes and links. Projections of water use and water balance are then calculated at each node to simulate the effects of water diversions, water apportionments, impacts of water price on water use, model reservoir operations, water use priorities, and water rationing (Beckers et al., 2009). Water use projections and the effects of climate change on irrigation have been investigated using WUAM in the South Saskatchewan River Basin (Kassem et al., 1994). Effects of both upstream development and water-use on reservoir levels in Lake Diefenbaker and its subsequent recreational value have also been modelled using WUAM (Kassem et al., 1994). Hardware/software requirements are minimal, as WUAM functions off any computer without the need for third-party software (Beckers et al., 2009). WUAM does not have a built-in GUI; therefore, familiarity with its Fortran-77 programming language is required. WUAM is not capable of linking to other models and all 16 modules of WUAM are not linked either. The model was developed in a sequential fashion and modules must be run separately (Kassem, 1992).

WUAM functions at monthly time steps; it is not specified whether it can solve time steps simultaneously or individually. WUAM is flexible with river basin configuration, yet is limited to a maximum of 50 network nodes in a single schematic (Kassem, 1992). In terms of data inputs, WUAM only accepts 21 pre-established data files (Kassem, 1992). WUAM does not simulate hydrologic processes such as runoff (Beckers et al., 2009), so incorporates hydrometric observations or simulated streamflow from other models. Other types of data that the model requires include precipitation, evapotranspiration, water demand curves, thermal power, hydro power, and irrigation area (Kassem, 1992).

Model outputs are provided in graphical and tabular format. Output is organized into a monthly/yearly/irrigation season basis and includes basic statistics for shortages and consumption at each node, water balance results at each node, and water demand summaries by category (Kassem, 1992). A series of optional outputs are available as well and detail basic statistics relating to irrigation

(moisture balance, monthly diversions, return flows), reservoir operation (reservoir levels and releases), thermal power (water use requirements), and hydro power (monthly power generation) (Kassem, 1992). WUAM has been developed and tested on the Saskatchewan River basin (Kassem, 1992); therefore, may be a candidate model for the ARB Project. However, considering that each of the 16 modules within WUAM is run as a separate program and that it lacks a graphical user-interface, it might not be considered the best modelling tool to actively engage stakeholders in the watershed management process or link with other tools as part of the ARB Project.

3.6 WEAP

The Water Evaluation and Planning System (WEAP) was developed by the Stockholm Environment Institute's US Center. WEAP is not an open-source model; for a non-consulting user it costs $3,000 for a 2 year license; however, other fees are associated for consultants. Support provided for the WEAP model is extensive; video tutorials, workshops and training courses, as well as a detailed user manual are all available on the WEAP webpage.

WEAP is a node and link river systems model designed to simulate water demand, supply, flow, storage, pollution generation, treatment, and discharge in order to evaluate a range of potential water-use scenarios (Sieber & Purkey, 2011). WEAP is a flexible model that can function on virtually any time-step for input data, as well as variable spatial scales from small community watersheds to large trans-boundary basins (Sieber & Purkey, 2011). WEAP uses a linear program optimization solver (Sieber & Purkey, 2011). It can be linked with Microsoft Excel and Word, and it is set-up to be linked with MODFLOW, MODPATH, QUAL2K, and PEST models (Sieber & Purkey, 2011). WEAP can also connect with external environmental databases, for example the USGS flow database for hydrological data input. It is coded in C++ and Delphi programming language; however, it is not required that the user is familiar with this code as there is a functional GIS-based GUI built into the model (Sieber & Purkey, 2011). WEAP has fast run times; average processing time is on the order of seconds to minutes. Input data do not usually require pre-processing and can be uploaded to the model via text file, or directly via the GUI.

Key data inputs include supply and demand data for initial conditions, basic water requirements for demand sites, existing water uses, capital and operating costs, industry production projections, population projections, irrigation land area and activity parameters, wastewater treatment parameters, hydropower generation parameters, climate data, hydrology data groundwater recharge rates, wastewater routing, water costs, maximum allowed concentrations for water constituents, pollution intensity levels and water temperature (Sieber & Purkey, 2011).

Model outputs are calculated at a monthly basis and include "demand site requirements and coverage, streamflow, instream flow requirement satisfaction, reservoir and groundwater storage, hydropower generation and energy demands, evaporation, transmission and return flow losses, wastewater treatment, pollution loads, and cost" (Sieber & Purkey, 2011). Results can be displayed at a monthly or yearly time step. WEAP can also simulate catchment processes such as infiltration, evapotranspiration, and runoff. Results are displayed in graph, table, or map format and can be saved in spreadsheet, text,

or graphic files respectively. Results can then be integrated in custom reports. Model output also includes various statistics but lacks Monte Carlo sensitivity analysis capability.

WEAP is a user-friendly model, and although its primary function is not stakeholder engagement, it has been used for such purposes in the past (WEAP, n.d). WEAP has yet to be applied in the ARB or Boreal regions of Canada. However, it has been widely used elsewhere in North America and abroad. This model has been used for state-wide water planning programs, studying climate change effects in the San Francisco Bay watershed, managing hydro power in the Sierra Nevada Mountains, managing Chinook Salmon in California's riverine ecosystems, and developing climate change adaption strategies in the Sacramento Basin and agricultural adaption strategies in the San Joaquin Valley (WEAP, n.d).

3.7 Model Ranking

A model ranking scheme was developed to compare the selected river systems models to various evaluation criteria. The models were ranked numerically based on the seven categories described below:

1. Model Type – type of algorithm it uses. Rank [0-1]; 0 for no information, 1 for linear programming.
2. License Cost – price of acquiring the model. Rank [0-1]; 0 for any associated cost beyond its use in the project, 1 for a free model.
3. Model Support – technical support and documentation (i.e. manuals, sample runs, workshops, etc…). Rank [0-1]; 0 for limited supporting materials, 1 for available materials.
4. Computing – based on ease of use (i.e. does it have a GUI?), model simulation time (i.e. is it fast?), ability to link to environmental databases, and capacity for multiple time step optimization. Rank [0-4]; 0 for none of the above, 1 for only meeting one of the criteria, 2 for meeting two, 3 for three, and 4 for meeting all criteria.
5. Model Scales – based on model time step and spatial planning scale. Rank for time step [0-2]; 0 for yearly time steps, 1 for monthly, and 2 for daily/weekly time steps. Rank for planning scale [0-1]; 0 for no information or local scale, 1 for flexible scales or basin-wide scales. Total Rank [0-3]; Sum of time step rank and planning scale rank
6. River System Components – based on the following questions: 1) Does the model accept non-hydrology data (i.e. economic, energy generation, etc…)? 2) Does the model represent allocation priorities? 3) Does the model conduct channel routing? Rank [0-3]; one point for each "yes" answer to the above questions.
7. Stakeholder Engagement – model's allowance for stakeholder engagement. Rank [0-3]; 0 for no stakeholder engagement, 3 for actively engaging stakeholders

The total score gives the sum of all ranked criteria out of 16. The categories and associated points for each model are presented in
Table 20.

Table 20: Ranking scheme for River System models

Categories	REGUSE	OASIS	WRMM	HCMS	WUAM	WEAP
Model Type (Max = 1)	1	1	1	1	0	1
License Cost (Max=1)	0	1	1	0	1	0
Model Support (Max=1)	0	1	0	0	0	1
Computing (Max=4)	0	4	2	0	0	3
Model Scales (Max=3)	2	3	3	0	2	2
River System Components (Max=3)	2	3	2	0	2	2
Stakeholder Engagement (Max=3)	0	3	0	0	0	2
Total (Max=16)	5	16	9	1	5	11

The relative order of all the models ranked from highest to lowest is OASIS > WEAP > WRMM > WUAM = REGUSE > HCMS. What differentiated OASIS from the others was its flexibility, ability to employ channel routing to multiple time step optimization as well as its capacity to engage stakeholders. Based on this review, it is recommended that OASIS be used for the ARB Project.

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Appendix A: Additional tables and details for the review of hydrological models

Table A1: Model summary

MODEL NAME	ACRU	CRHM	HBV-EC	HEC-HMS	HSPF	HGS	MIKE-SHE	RAVEN	RHESSYS	SWAT	VIC	WATFLOOD
MODEL TYPE	Semi-Distributed	Semi-Distributed	Semi-Distributed	Semi-Distributed	Semi-Distributed	Fully-Distributed	Fully-Distributed	Flexible	Semi-Distributed	Semi-Distributed	Macroscale	Semi-Distributed
LICENSE COST	Small Fee	No	No	No	No	No	Yes	No	No	No	No	Yes
COMPUTING												
Equipment	PC, GIS	PC, Mac, GIS, Excel	PC	PC, UNIX, Linux, GIS	Unix, DOS, GIS	PC	PC	PC, Linux	PC, GIS	PC, Unix, GIS	UNIX, Linux, GIS	PC
GUI	Within Model	Within Model	Green KenueTM	Within Model	Within Model	None	Within Model	Green KenueTM	None	ArcSWAT	None	Green KenueTM
Open Source	No	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	No
Link Environ. Databases (e.g. HYDAT)	No	Yes	Yes	No	No	No	No	Yes	No	Yes	No	Yes
MODEL SCALE												
Time Step	Daily	Hourly	Daily	Hourly or greater	Minute to Daily	Variable	Variable	Hourly or greater	Daily	Daily	Hourly	Hourly
Planning Scale	Sub-basins	HRUs	GRUs	Sub-basins	Lumped	Distributed	Distributed	HRUs	Heirarchical	Heirarchical	Statistical	GRUs
MODEL INTEGRATION ABILITY												
Model has been integrated with others	Yes	Yes	Yes	Yes	Yes	NIF	Yes	Yes	Yes	Yes	Yes	Yes
KEY HYDROLOGIC PROCESSES												
Rain Interception	E	P	E	E	E	E	E	P-F	E	E	E	E
Snow accumulation	E	P	E	E	E	E	E	E-F	E	E	E	A
Snowmelt	E	P	E	E	E-P	E	E	E-P-F	A	E	P	A
Snow Interception	E	P	E	NA	E	NA	E	P-F	E	E	P	E
Sublimation	E	P	E	NA	E	Y	E	P-F	E	NIF	P	E
Evapotranspiration	P	P	E	E	E	A	A	E-P-F	P	E-P	P	E
Evaporation	P	P	E	E	E	A	E	E-P-F	P	E-P	P	E
Infiltration	E	A	E	E-P	E-A	P	A	E-A-F	E	E	E	A
Overland flow	E	A	A	E	E	P	P	A-F	E	E	P	A
Subsurface Hillslope Runoff	E	A	E	E	E	P	P	E-F	E	E	E	E
Groundwater Flow	E	E	E	E	E	P	P	E-F	E	P	E	E
Glacier Melt	E	A	E	NA	NA	NA	E	E-F	Y	Y	NA	E
Frozen Soil	NIF	E	NA	NA	NA	A	NA	E-F	NIF	Y	E	NA
Lake Storage	A	A	A	E	A	A-P	E	A-F	NIF	A	A	A
Peatland	Y	A	NA	E	NA	Y	A	E-F	Y	A	E	E

A = Analytical
E = Empirical
P = Physically based
NA = Not available in model
NIF = No information found
Y = Incorporates process but no documentation found
F = Flexible

Table A2: Model descriptions

Model	Development Group	Model Information					
		URL	Manual	Tutorial (sample runs?)	Workshops/ Training Courses	Support	Cost
ACRU	University of Lethbridge (University of Natal in South Africa)	http://dbnweb2.ukzn.ac.za/unp/beeh/acru/information/infoFrame.htm	Yes	No	No (UofL ACRU)	None	Small fee?
CRHM	University of Saskatchewan	http://www.usask.ca/hydrology/CRHM.php	Yes	No	Yes	Limited	None; Academic agreement
HBV-EC	Modified by Environment Canada	http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/green_kenue_index.html	Yes	Yes	No	Limited	None
HEC-HMS	US Army Corps of Engineers	-	Yes	Yes	Yes	None	None
HSPF	US Geological Survey	http://water.usgs.gov/software/HSPF/	Yes	Yes	Yes (Aqua Terra	USGS HSPF user list server	None
HGS	University of Waterloo	http://www.aquanty.com/about-us-hgs/hgs-technology/	Yes	Not found	Yes	Limited (HGS Community)	None; Academic agreement
MIKE-SHE	DHI Water & Environment	http://www.mikebydhi.com/products/mike-she	Yes	Yes	Yes	Yes	$28000-8000; maintain ($3500-4800)
RAVEN	University of Waterloo	http://www.civil.uwaterloo.ca/jrcraig/Raven/Main.html	Yes	No	No	Limited	None
RHESSYS	UC Santa Barbara	http://fiesta.bren.ucsb.edu/~rhessys/	Yes	Yes	No	Limited	None
SWAT	Texas A&M University; USDA Agriculture Research Service	www.brc.tamus.edu/swat/index.html	Yes	Yes	Yes	Limited	None
VIC	University of Washington	www.hydro.washington.edu/Lettenmaier/Models/VIC/	Limited (web pages)	No	No	VIC Support User List	None
WATFLOOD	University of Waterloo	www.civil.uwaterloo.ca/Watflood/intro/intro.htm	Yes	Yes	No	Limited	Yes ($2000?)

Table A3: Computing requirements

Model	Computing Requirements				
	Equipment/ Software	GUI	Open Source	Link Environ. Databases (e.g. HYDAT)	Model Simulation Time
ACRU	PC, GIS	Within Model	No	-	hours
CRHM	PC, Mac, GIS, Excel	Within Model	Yes	-	minutes
HBV-EC	PC	Green KenueTM	No	Yes	minutes
HEC-HMS	PC, UNIX, Linux, GIS	Within Model	No	-	minutes
HSPF	Unix, DOS, GIS	Within Model	No	-	hours
HGS	PC	None	Yes	-	minutes
MIKE-SHE	PC	Within Model	No	-	hours
RAVEN	PC, Linux	Green KenueTM	Yes	Yes	minutes
RHESSYS	PC, GIS	None	Yes	-	minutes
SWAT	PC, Unix, GIS	ArcSWAT	Yes	-	hours
VIC	UNIX, Linux, GIS	None	Yes	-	hours
WATFLOOD	PC	Green KenueTM	No	Yes	minutes

Table A4: Model scales

Model	Model Type	Model Scales			Applied in ARB OR Boreal Plain
		Time Step	Planning scale	Application scale[1]	
ACRU	Semi-Distributed	Daily	Sub-basins	Small to medium	Yes
CRHM	Semi-Distributed	Hourly	HRUs	Small to medium	Yes
HBV-EC	Semi-Distributed	Daily	GRUs	Small to medium	No
HEC-HMS	Semi-Distributed	Hourly or greater	Sub-basins	Small to medium	No
HSPF	Semi-Distributed	Minute to Daily	Lumped	Small to large	Yes
HGS	Fully-Distributed	Variable	Distributed	Small to large	Yes
MIKE-SHE	Fully-Distributed	Variable	Distributed	Small to large	Yes
RAVEN	Flexible	Hourly or greater	HRUs	Variable	No
RHESSYS	Semi-Distributed	Daily	Heirarchical	Small to medium	No
SWAT	Semi-Distributed	Daily	Heirarchical	Small to large	Yes ($SWAT_{BF}$)
VIC	Macroscale	Hourly	Statistical	Medium to large	Yes
WATFLOOD	Semi-Distributed	Hourly	GRUs	Small to large	Yes

[1]Application scale (from Beckers et al., 2009): small (<100 km^2); medium (100 - 10,000 km^2); large (>10,000 km^2)

Table A5: Model inputs and outputs

	Key Required Inputs (not a complete list)					Model Outputs															
Model	Map Files	Met Data	Veg	Soil Parameters	Routing	full hydrograph	Annual Yield	Peak Flow	Low Flow	SWE	ET	Water Balance	Soil Moisture	Infiltration	Water Table	Overland Flow	Subsurface Storage Runoff	Groundwater/Baseflow	Watershed Runoff	Other
ACRU	DEM, land classification, soil depth, and texture classes	Daily P, min and max air T	Crop type	Soil texture, hydraulic conductivity, root depths	Slope, length, roughness, shape	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Sediment erosion, nutrient fluxes; irrigation, reservoir operations
CRHM	Spatial data (basin area, DEM) imported/generated with internal GIS tools	Variable, depending on specific selections within CRHM (P, T, Q, RH, wind speed and direction)	Veg height, albedo, fetch distance (no understory parameters)	Lag time, storage constant, ground slope, thickness, bulk density, porosity, heat capacity, soil moisture conditions, hydraulic conductivity	Lag time, storage constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Effect of frozen soil on water movement
HBV-EC	DEM, land classification (forest, open, lake, glacier)	Daily P, daily mean air T, daily PET, correction factors for elevation and gauge errors	Canopy factors for sunlight blocked, interction fraction, ratio of melt compared to open areas (no understory)	Empirical reservoir parameters, field capacity, lower limit for ET	Linear reservior parameters	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Glacial melt, lakes
HEC-HMS		Meteorological data are input to a meteorological model that may be applied in a gridded or Theissen polygon approach to the model area; data may originate from specific gauges stations or be generated statistically based on required storm frequency and exceedance probability (US National Weather Service data)	Crop coefficient for distribution of vegetative cover within model area (N/A understorey parameters)	Linear reservoir parameters for baseflow store; depends on complexity of modelling, soil moisture curves (vanGenuchten functions, Brooks-Corey functions, or tabulated relationships for capillary pressure-moisture content and relative permeability)	depends on complexity of modelling	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Lakes, wetlands, parameter estimation, depth-area analysis, flow forecasting, erosion and sediment transport, and nutrient water quality
HSPF	DEM, pervious or impervious land segments with similar hydrological characteristics	Precipitation and temperature as minimum; temperature lapse rate is optional if defaults are not good; solar radiation, dew point, wind velocity, and cloud cover are needed for energy-based snowmelt calculations	Canopy interception capacity (monthly or constant), PET, lower zone ET fraction, base flow ET fraction, Manning's roughness co-efficient for surface runoff, shaded fraction of land segment (snowmelt calculations) fraction of land covered by forest	Upper zone storage, lower zone storage nominal, porosity, infiltration index, infiltration exponent, infiltration ratio, lengthof-surface flow path, slope-of-surface flow path, surface retention storage, upper zone storage nominal, interflow index, interflow recession constant, seriable groundwater recession, active groundwater recession constant, fraction of groundwater to deep aquifer or inactive storage, and active groundwater ET fraction	Length, width, depth and hydraulic properties of each reach, hydraulic routing weighting factor	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Water quality - tillage practices may be needed as input
HGS	DEM, geologic layering, vegetative cover	Climate data pre-processed to generate rainfall and PET data for use in model	LAI, field capacity, wilting point, evac and anoxic limits, interception value, root density function, root depth, three fitting parameters	Hydraulic conductivity, specific storage, porosity, anisotropy ratio,	Manning's N, microtopography height, minimum mobile water depth	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Water quality
MIKE-SHE	DEM, soil type, geologic layering, vegetative cover	Temperature, precipitation, PET	Overstory - LAI, field capacity, wilting point, interception value, root zone depth, three fitting parameters; understory - Lumped with overstorey vegetation (i.e., one vegetation layer)	Hydraulic conductivity, specific storage, porosity, anisotropy ratio, built-in soil database with pedo-transfer functions; user may specify soil moisture curves (vanGenuchten functions, Brooks-Corey functions, or tabulated relationships for capillary pressure-moisture content and relative permeability)	Explicit connection to river/stream reaches when using linear reservoir approach; runoff routed to rivers by 2D overland flow; river flow calculated by MIKE-11 in parallel to MIKESHE simulation (by Muskingum routing to the Higher Order Dynamic Wave formulation of the Saint-Venant equations)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Water quality
RAVEN	DEM	MINIMUM: Precipitation, max and min temperature	Dependent on complexity			Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Glacier melt
RHESSYS	DEM, hillslope, soil types, LAI, slope, aspect, impervious, land use, vegetation	Daily precipitation, daily maximum and minimum temperatures; can also download data from NCDC	Trunk space, height, LAI, albedo, aerodynamic attenuation, radiation attenuation, clumping factor, maximum snow interception capacity, maximum release drip ratio, snow interception efficiency, stomatal resistance (min/max), moisture threshold, vapor pressure deficit, RHC, number of root zones, root zone depths, root fractions in each zone; Understorey parameters (LAI, albedo, root fractions in each zone)	Lateral conductivity and exponential decrease, porosity, surface albedo, vertical conductivity, porosity, maximum infiltration, pore size distribution, bubbling pressure, field capacity, wilting point, bulk density, thermal conductivity, thermal capacity	Stream network file, stream map file, stream class file, road network file, road map file, road class file, unit hydrograph, and travel time files (last two files replace need for all preceding files)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Nutrient fluxes
SWAT	DEM, landuse/land cover	Daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity; can be from observed data records or generated during simulation	LAI, canopy height, root depth, stomatal conductances, nitrogen uptake parameters; understory parameters: N/A	Deep aquifer percolation fraction, specific yield, groundwater delay time, recharge delay time, baseflow recession constant, soil hydrologic group, root depth, water capacity, hydraulic conductivity, percent sand/silt/clay, texture	Users are required to define the width and depth of the channel when filled to the top of the bank as well as the channel length, side slope, and Manning's N	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Sediment erosion, nutrient fluxes, water quality
VIC	DEM, land cover, soil type	At a minimum temperature and precipitation at model input time step; additional meteorological data (atmospheric density and pressure, shortwave radiation, vapor pressure, wind speed) can also be specified as model input; alternatively they are calculated internally in model	Number of vegetation types in grid cell, fractions of grid cell covered by vegetation type, number of root zones, root zone thicknesses, root fraction in each zone, LAI (one per month), flag for overstorey present, architectural resistance, minimum stomatal resistance, shortwave albedo, roughness length, displacement height, shortwave radiation ET threshold, radiation attenuation factor, wind attenuation, trunk ratio	VI curve , max baseflow velocity, fract of max velocity where non-linear baseflow begins, fract of max soil moisture where non-linear baseflow occurs, baseflow exponent, saturated hydraulic conductivity, exponent for variation of conductivity with soil moisture, soil moisture diffusion parameter, moisture content, average soil temperature, soil thermal damping depth, bulk density, field capacity, wilting point, residual moisture content, soil roughness	Flow direction file, flow velocity file, flow diffusion file; grid cell contributing fraction	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	None
WATFLOOD	DEM	Temperature, rain/snow gauge data (or radar data), radiation data	Forest vegetation coefficient for PET-AET reduction (tall versus short vegetation); interception fractions; understorey (Lumped with overstorey vegetation (i.e., one vegetation layer)	Empirical parameters, soil moisture and temperature coefficients for PET-AET reduction, depth and resistance of interflow layer	Channel roughness, bankfull versus drainage table	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	None

Built from:

Beckers, J., Smerdon, B., & Wilson, M. (2009). Review of hydrologic models for forest management and climate change applications in British Columbia and Alberta. FORREX Forum for Research and Extension in Natural Resources, Kamloops, BC. FORREX Series No. 25. British Columbia, Canada .

Table A6: Hydrologic process representation

Model	Hydrologic Processes														
	Rain Interception	Snow accumulation	Snowmelt	Snow Interception	Sublimation	ET	Evaporation	Infiltration	Overland flow	Subsurface Hillslope Runoff	Groundwater Flow	Glacier Melt	Frozen Soil	Lake Storage	Peatland
ACRU	E	E	E	E	E	P	P	E	E	E	E	E	NIF	A	Y
CRHM	P	P	P	P	P	P	P	A	A	A	E	A	E	A	A
HBV-EC	E	E	E	E	E	E	E	E	A	E	E	E	NA	A	NA
HEC-HMS	E	E	E	NA	NA	E	E	E-P	E	E	E	NA	NA	E	E
HSPF	E	E	E-P	E	E	E	E	E-A	E	E	E	NA	NA	A	NA
HGS	E	E	E	NA	Y	A	A	P	P	P	P	NA	A	A-P	Y
MIKE-SHE	E	E	E	E	E	A	E	A	P	P	P	E	NA	E	A
RAVEN	P	E	E-P	P	P	E-P	E-P	E-A	A	E	E	E	E	A	E
RHESSYS	E	E	A	E	E	P	P	E	E	E	E	Y	NIF	NIF	Y
SWAT	E	E	E	E	NIF	E-P	E-P	E	E	E	P	Y	Y	A	A
VIC	E	E	P	P	P	P	P	E	P	E	E	NA	E	A	E
WATFLOOD	E	A	A	E	E	E	E	A	A	E	E	E	NA	A	E

where E - empirical, A - analytical, P - physical, NA - not available in model, NIF - no information found, Y - incorporates process, but no information found

Appendix B: Additional tables and details for the review of land use models

Table B1: Model descriptions

Model	Development Group	Model Information					
		URL	Manual	Tutorial (sample runs?)	Workshops/ Training Courses	Support	Cost
ALCES	ALCES Group	http://www.alces.ca/	Yes	Yes	Yes	Yes	None
LTM	Purdue University	http://ltm.agriculture.purdue.edu/default_ltm.htm	None found	Yes	None found	Limited	None
SELES	Simon Fraser University	http://gowlland.ca/about_gowlland/index.html	None found	None found	Not specified	Limited	unknown
CanWET	Greenland Technologies Group	http://www.grnland.com/index.php?action=display&cat=17	Yes	Yes	Available	Yes	unknown
NetLogo	Developed by Uri Wilensky	https://ccl.northwestern.edu/netlogo/docs/	Yes	Yes	Available	Yes	None
TELSA	ESSA Technologies LTD	http://www.essa.com/tools/telsa	Yes	Yes	Yes	Yes	None
What if?	What if Inc.	http://www.whatifinc.biz	Yes	Yes	None found	Limited	None (model support is an extra charge)

Table B2: Computing requirements

Model	Computing Requirements								
	Equipment / Software	GUI	Operating System	Open Source	Link Environ. Databases & HDAT)	Link to other models?	Model Simulation Time	Easy-to-learn programming language?	Can model be refined/improved (time/costs necessary?)
ALCES	PC running MS Windows OS, licensed copy of Stella, MS Excel, Adobe Reader, GIS	Yes	Windows or MacIntosh	No	Uses information from external databases, but is not directly linked to them	Yes - OASIS, EwE, CSIRO in AU	minutes	code is locked off to prohibit inadvertent modifications	Not specified
LTM	PC running on Windows, ArcGIS software, Excel, MS Access	No	Windows	Yes	Not specified	No	minutes	GIS portion of LTM is coded in ArcView 3.2 Avenue scripting language. A collection of routines written in C is used to process and analyze data.	Not specified
SELES	uses PAMAP GIS directly as a spatial database and third party landscape statistics package, FRAGSTAT	Yes	Windows	Not specified	Not specified	Yes (Mountain Pine Beetle Model)	300-year simulation in 10 minutes	No programming language needed due to GUI	Not specified
CanWET	PC, Open source GIS based application called MapWindow	Yes	Windows	Not specified	Yes	Not specified	minutes	No programming language needed due to GUI	Not specified
NetLogo	Cross platform (runs on Mac or Windows PC) - with QuickTime Bitmap and GIS extensions	Yes	Windows or MacIntosh	Yes	Not specified	Yes	minutes	No programming language needed due to GUI	Not specified
TELSA	PC, ArcGIS, VDDT	Yes	32-bit OS (Windows 2000 or Windows XP)	Yes	Not specified	Yes via ArcGIS platform	minutes	ArcGIS scripting language	Not specified
What if?	PC, Windows OS and ArcGIS	Yes	Windows	No	uses information from external databases but not directly linked	Not specified	minutes	No programming language needed due to GUI	Not specified

Table B3: Model scales

Model	Model Type	Model Scales			
		Time Step	Spatial scale[1]	What is the finest resolution it can model?	Applied in ARB
ALCES	Cell based modelling with multiple components	Variable	Variable	Anything data can support	Yes
LTM	Neural Network based	Variable	Variable	Whatever the data can support	No
SELES	raster based model using probabilistic disturbance spreads	Variable	Variable	Whatever the data can support - but each cell is assumed to be spatially and compositionally homogeneous	No
CanWET	GIS based watershed management tool with land-use functionalities	Daily	Variable	provides output results at watershed level	No
NetLogo	Agent based modelling	Variable (SAOSRSA model is annual)	Variable	Whatever the data can support	Yes - SAOSRSA
TELSA	GIS based landscape model of vegetation dynamics	decades to centuries	regional landscape scale	Anything the data can support	No
What if?	GIS based planning support system	Yearly or greater	city to regional scale	Whatever the data can support	No

Table B4: Model inputs and outputs

Model	Key Required Inputs (not a complete list)							Model Outputs		
	Hydrology component?	Climate change impacts?	Economic drivers?	Supports user-defined input?	File format?	Can model run over time data?	Max number of inputs?	Graphical output?	Map output?	Statistical Analysis or Monte Carlo?
ALCES	Yes	Yes	Yes	Yes	Excel input data files, GIS for ALCES mapper	Not specified	Max of 20 landscape types, 15 footprint types, 15 input/output rates, 6 population types and 12 transport activities,	Yes	Yes - GIS layer based	Yes - Monte Carlo sensitivity analyses
LTM	Yes	Not specified	Yes	Yes	"ascii" file type	not without significant modifications	Not specified	No	Yes - GIS based	Gives Percent Correct Metric (PCM) and Kappa statistic in text file
SELES	Yes	Yes	Not specified	Yes	A variety of raster layer formats (GRASS, ERDAS, and ARC ASCII)	not without significant modifications	Not specified	No, but can export to spreadsheet programs	Yes - raster based	Yes - Monte Carlo simulations
CanWET	Yes	Yes	Yes	Not specified	not specified	Not specified	Not specified	Yes	Yes	no
NetLogo	Yes	Yes	Yes	Yes	not specified	Not specified	Not specified	Yes	Yes	Not specified
TELSA	No	Yes	Not specified	Yes - for certain criteria	GIS vector format	Not specified	Not specified	Yes	Yes	Yes - Monte Carlo
What-if?	Not specified	Not specified	Not specified	Yes	UNION file	Not specified	Max of 30 land use types, and 20 suitability layers	No	Yes	No

Table B5: Represented land uses/natural disturbance

Model	Natural Processes				Human Land Uses						
	Fire (constant, random)	Insects (constant or random)	Climate change (contant, random)	Water metrics	Forestry?	Energy Sector?	Mining?	Municipal Development?	Agriculture?	Other types of landuse...	Can stakeholders participate in the model building and validation process?
ALCES	Y,Y	Y,Y	Y,Y	Yes	Yes	Yes	Yes	Yes - in the form of urban and industry development	Yes - in the form of cropland, aquaculture, and livestock	GIS-based so any spatial data can be used	Yes - this is the main goal and component of ALCES approach
LTM	Not specified	Not specified	Not specified	Yes	Yes	Not specified	Not specified	Yes - urban expansion	Yes	GIS-based so any spatial data can be used	No - Not user friendly
SELES	Y, Y	Y, Y	N,Y	Y	Yes	Not specified	Yes	Yes	Yes	GIS-based so any spatial data can be used	No
CanWET	Not specified	Not specified	Y, N	Y	Yes	Not specified	Yes	Yes	Yes	GIS-based so any spatial data can be used	Not explicitly specified
NetLogo	Y, Y	Y, Y	Y, Y	Y	Yes	Yes	Yes	Yes	Yes	User defined input supported	Not explicitly specified
TELSA	Y,Y	Y,Y	Y, N	limited	Yes	Not specified	Not specified	Not specified	Not specified	sucessions and natural disturbances	Not explicitly specified
What if?	Not specified	Not specified	Not specified	Not specified	Yes	Yes	Yes	Yes	Yes	yes - 10 categories in total supported	Not explicitly specified

Appendix C: Additional tables and details for the review of river system models

Table C1: Model summary

MODEL NAME	REGUSE	OASIS	WRMM	HCMS	WUAM	WEAP
MODEL TYPE	Network flow approach using out-of-kilter optimization algorithm for linear programming	Arc and Node model using linear programming solver	Arc and Node model using linear programming solver	Semi-distributed model using IBM linear programming optimization	River Node model – optimization algorithm not specified	Node and link system with linear programming solver
LICENSE COST	-	No fee with hydrologics involvement OR fee without involvement	None	-	None	Yes
MODEL SUPPORT	-	Yes	Limited	-	Limited	Yes
COMPUTING						
Equipment	PC	Microsoft, XA solver	Microsoft, OKA or Lindo systems	-	PC	Microsoft Windows
GUI	-	Yes	No	-	No	Yes
Publically Available	-	Yes	Yes	-	Yes	No
Link Environ. Databases	-	Yes	Yes	-	-	Yes
Model simulation time	-	minutes	minutes	-	-	minutes
Multiple time step optimization?	-	Yes	No in general but a version exists	No	-	-
MODEL SCALE						
Time Step	D/M	variable	W	-	M	Monthly
Planning Scale	-	Flexible	Flexible	-	Flexible	River basins
Integrated with others?	-	possible	possible	-	No	Yes
RIVER SYSTEM COMPONENTS						
Non-hydrology data?	-	Yes	No	-	Yes	Yes
Allocation priorities?	Yes	Yes	Yes	-	Yes	Yes
Channel routing?	Yes	Yes	Yes	-	-	-
Previously used in ARB?	-	No	No	No	No	No
STAKEHOLDER ENGAGEMENT						
Facilitates stakeholder engagement?	No	Yes	No	-	-	Yes

Table C2: Model descriptions

Model	Development Group	Model Information					
		URL	Manual	Tutorial (sample run?)	Workshops/ Training Courses	Support	Cost
REGUSE	Environment Canada	-	Yes				-
OASIS	HydroLogics	http://www.hydrologics.net/oasis.html	Yes	Yes	Yes	Yes	No fee with Hydrologic's involvement OR fee without involvement
WRMM	Owned by Alberta ESRD	http://environment.alberta.ca/01745.html	Yes	-	Limited	ESRD support limited, industry support present	None
HCMS	Environment Canada	http://pubsonline.informs.org/doi/abs/10.1287/inte.10.4.79	Yes	Yes	Yes	None	-
WUAM	Environment Canada	http://publications.gc.ca/site/eng/41548/publication.html	Yes	Hypothetical example given in manual	No	Contact developer at atef.kassem@ec.gc.ca	None
WEAP	The Stockholm Environment Institute's U.S. Center	http://www.weap21.org/	Yes	Yes	Yes	Yes	3000$ for 2 year license for non-consulting user

Table C3: Computing requirements

Model	Computing Requirements							
	Equipment/ Software	GUI	Open Source	Link Environ.Databases (e.g. EPDM)	Link to other models?	Model Simulation Time	Easy to learn programming language?	Can model be easily expanded? (time/costs necessary?)
REGUSE	PC	-	-	-	-	-	-	-
OASIS	VEDIT, XA, Microsoft, MetaDraw, True DBGrid, Charting Tools and Real-Time Graphic Tools for Windows	Windows based	Yes	Yes	Yes	minutes	OCL - easier than C++ or Fortran	Yes
WRMM	PC, Microsoft Acces, OKA or Lindo Systems	A windows based GUI is under development in WRM-DSS version	Yes	Yes	possible - uses databases to lnk ouput to other models	minutes	uses C++, but not necessary to run model. Data is entered using specific syntax rules in text file mode	Yes
HCMS	-	-	-	-	-	-	-	-
WUAM	PC	No	Yes	-	No	Not specified - but all 16 modules run seperately	Fortran-77	-
WEAP	Can run on all versions of Microsft Windows. Can communicate with Excel and Word but not required	Yes - GIS-based	No	Yes - USGS flow database	Yes - MODFLOW, MODPATH, QUAL2K, PEST	minutes	Delphi and C++	Yes

Table C4: Model scales

Model	Model Type	Model Scales				Applied in ARB or Boreal
		Time Step	Multiple time step?	Planning scale	Application scale	
REGUSE	Network-flow approach	Daily, monthly	-	-	-	-
OASIS	Arcs and Nodes	Variable	Yes (has both STO and MTO)	Is flexible with river basin configuration	small and simple to large and complex	Yes - BRP within Boreal Plains Ecoregion
WRMM	Arcs and Nodes	Developed for weekly, because max of 52 steps/cycle (52 weeks/year)	Only at steady state. Channel routing can only be used in STO mode, because no MTO mode is available	Is flexible with river basin configuration	River basin is fundamental unit of study	No
HCMS	Semi-Distributed	-	No	-	-	No
WUAM	River Nodes	Monthly	-	Is flexible with river basin configuration	Dendritic river networks	No
WEAP	Node and link system	Monthly	-	river basins	river basins	No

Table C5: Model inputs and outputs

Model	Key Required Inputs						Model Outputs			
	Hydrology components?	Other types of data? Ie. Economic drivers, policies, water quality, etc...	Supports user defined inputs?	input file formats	Can model use real-time data?	Max number of inputs?	Graphical output?	Map output?	Simple flow, storage, etc... output?	Statistical Analyses or Monte Carlo?
REGUSE	Yes	-	Yes	-	-	-	-	-	-	-
OASIS	Yes	Yes	Yes - GUI has locations for this input	Microsoft Acces, ASCII(plain text), HEC-DSS	possible but requires substantial modification	From industry perspective it is unknown. Hydrologics says 999 nodes	Yes - plotmaker tool gives Excel graph output	No?	Yes One-Var	Not directly - can run in "position analysis" mode allowing for probability analyses.
WRMM	Yes	No	Yes - but only hydrology inputs	text file	possible with interface and MTO mode	limited to 500-800 components. WRM-DSS is unlimited	output linked to MS Acces database to create graphs or excel spreadsheets	GUI in WRM-DSS uses GIS map underlay	Yes	No
HCMS	Yes	-	-	-	-	-	-	-	-	-
WUAM	Yes	Yes	No - only accepts 21 pre-established data files	DAT, CFS, 1-0	-	50 network nodes, 100 years of hydrologic records, etc...	Yes	No	No - only water demand, water balance and shortages	No
WEAP	Yes	Yes	Yes	text file	possible	28 nodes on main river, 65 demand sites, 60 years of hydrologic records, etc...	Yes	Yes - GIS based	Yes	Provides various statistics but not Monte Carlo

Table C6: River system representation

Model	River Systems Modeling processes						
	Can this model support decision making (real-time and long-term or only one of the two)	What kind of optimization solver does the model use? (+/+ linear programming	Can it represent allocation priority packs?	Restriction rules and hydro constraints?	Can stakeholders use the model directly? Is the model built with stakeholder process	How does it represent channel routing? Muskingum routing?	What time steps can be modelled?
REGUSE	Yes	"out-of-kilter" optimization algorithm	Yes - uses penalty coefficients	-	No -not directly, but they can incorporate input via experts	channel routing	Daily, monthly
OASIS	Yes - long term decision support. Currently developed as real-time decision support tool	XA Solver for LP and Mixed Integer Problems by Sunset Software Technology, Inc	Uses penalties for allocation priority but can't optimize them for policies	Yes	Yes - each model is built with active stakeholder engagement	Muskingum routing - however coefficients are limited to due to variations in flow	Daily, weekly, monthly
WRMM	WRM-DSS is being developed for this	WRMM uses OKA (Out-Of-Kilter Algorithm) for LP. WRM-DSS uses Lindo Systems mixed integer barrier solver version 6 (for Non LP?)	Uses penalties for allocation priority but can't optimize them for policies	Yes in single time steps only	No direct stakeholder interaction - requires user friendly interface	Problem arises with daily runs. Can use muskingum, but only uses static coefficients	Weekly and Monthly. Daily is possible but to a max of 52 days
HCMS	-	IBM linear programming optimization routine DOSPR of the package SL-MATH	-	-	Not specified	-	-
WQAM	Yes - can support long term decision making	-	Uses a decision hierarchy and priority ranking system	Yes	Not specified	Stream routing?	Monthly, Yearly
WEAP	Yes	open source linear program solver called LPSolve	Yes - based on demand priorities, supply preferences, and allocation order	Yes	Yes	problem only arises when using daily timestep	Daily, Monthly, Yearly - provides monthly analysis