Hydrologic model selection for the CFCAS project: Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions

Project Report I.

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I. INTRODUCTION

The main purpose of this report is to present an up-to-date summary and comparison of existing hydrologic models that are potentially suitable for achieving the goals set in the Canadian Foundation for Climatic and Atmospheric Sciences (CFCAS) funded project "Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions" ("project" hereafter). The report is intended to provide the information necessary for choosing the "right" model; a model which would be the most appropriate hydrologic modeling tool for the project in terms of various criteria. A two-level selection approach is used to objectively determine the most suitable model. At the first level a large number of existing hydrologic models are reviewed according to four fundamental selection criteria, and a subset of 18 models is identified. The selected 18 models are then ranked according to several evaluation criteria reflecting different aspects of specific project's requirements. At the second level, total ranks attributed to the 18 selected models serve as an objective measure for determining the most appropriate model(s).

The structure of the report is following: the next section introduces the basic terminology and classification of hydrologic models used in this report. The following section then summarizes the main selection criteria derived from the project requirements on hydrologic model outputs, hydrologic processes that need to be modeled in order to estimate the required outputs adequately, availability of input data, and costs related to the use of the model. This is followed by a short description of the selected hydrologic models. The last section explains the model evaluation criteria, compares the selected models according to these criteria, and provides recommendations for the final model selection.

II. CLASSIFICATION OF HYDROLOGIC MODELS

This section introduces the classification of existing hydrologic models and the terminology related to hydrologic modeling, which has been adopted in this report. Without going into too much detail, deterministic hydrologic models can be classified into three main categories:

1. ***Lumped models***. Parameters of lumped hydrologic models do not vary spatially within the basin and thus, basin response is evaluated only at the outlet, without explicitly accounting for the response of individual subbasins. Parameters of lumped models often do not represent physical features of hydrologic processes and usually involve certain degree of empiricism. The impact of spatial variability of model parameters is evaluated by using certain procedures for calculating effective values for the entire basin. The most commonly employed procedure is an area-weighted average (Haan et al., 1982). Lumped models are not usually applicable to event-scale processes. If the interest is primarily in the discharge prediction only, then these models can provide just as good simulations as complex physically based models (Beven, 2000).
2. ***Semi-distributed models***. Parameters of semi-distributed (simplified distributed) models are partially allowed to vary in space by dividing the basin into a number of smaller subbasins. There are two main types of semi-distributed models: 1) kinematic wave theory models (KW models, such as HEC-HMS), and 2) probability distributed models (PD models, such as TOPMODEL). The KW models are simplified versions of the surface and/or subsurface flow equations of physically based hydrologic models (Beven, 2000). In the PD models spatial resolution is accounted for by using probability distributions of input parameters across the basin.

3. ***Distributed models***. Parameters of distributed models are fully allowed to vary in space at a resolution usually chosen by the user. Distributed modeling approach attempts to incorporate data concerning the spatial distribution of parameter variations together with computational algorithms to evaluate the influence of this distribution on simulated precipitation-runoff behaviour. Distributed models generally require large amounts of (often unavailable) data for parameterization in each grid cell. However, the governing physical processes are modeled in detail, and if properly applied, they can provide the highest degree of accuracy.

According to the hydrologic processes modeled, hydrologic models can be further divided into event-driven models, continuous-process models, or models capable of simulating both short-term and continuous events. Event-driven models are designed to simulate individual precipitation-runoff events. Their emphasis is placed on infiltration and surface runoff, their objective is the evaluation of direct runoff. Typically, event models have no provision for moisture recovery between storm events and, therefore, are not suited for the simulation of dry-weather flows (drought analyses). Continuous-process models on the other hand take explicit account of all runoff components, including direct and indirect runoff. They focus on long-term hydrologic abstractions responsible for the rate of moisture recovery during the periods of no precipitation. They are suited for simulation of daily, monthly or seasonal streamflow, usually for long-term runoff-volume forecasting and for estimates of water yield (Ponce, 1989).

III. MODEL SELECTION CRITERIA

There are numerous criteria which can be used for choosing the "right" hydrologic model. These criteria are always project-dependent, since every project has its own specific requirements and needs. Further, some criteria are also user-depended (and therefore subjective), such as the personal preference for graphical user interface (GUI hereafter), computer operation system (OS), input-output (I/O) management and structure, or user's add-on expansibility. Among the various project-depended selection criteria, there are four common, fundamental ones that must be always answered:

1. required model outputs important to the project and therefore to be estimated by the model (Does the model predict the variables required by the project such as peak flow, event volume and hydrograph, long-term sequence of flows, …?),
2. hydrologic processes that need to be modeled to estimate the desired outputs adequately (Is the model capable of simulating regulated reservoir operation, snow accumulation and melt, single-event or continuous processes, …?),
3. availability of input data (Can all the inputs required by the model be provided within the time and cost constraints of the project?),
4. price (Does the investment appear to be worthwhile for the objectives of the project?).

(1) The CFCAS project is aimed at assessing the potential impact of climate change on a wide range of hydrologic processes and existing water management practices. The following hydrologic model outputs are required in order to fulfill the project objectives:

- simulated flow peaks (stage, discharge), volumes and hydrographs at the outlets of subbasins, and in the profiles of special interest within the main basin such as reservoirs, weirs or other hydraulic structures,

- simulated long flow sequences for water budget and drought analyses primarily for the main basin, but preferably also for the individual subbasins,
- simulated extend of flooded areas for different precipitation events and various antecedent basin conditions.

(2) The main hydrologic processes that need to be captured in the structure of the hydrologic model in order to adequately estimate the required project's outputs are:

- single-event precipitation-runoff transformation based on various antecedent basin conditions and spatial and temporal precipitation distribution,
- continuous precipitation-runoff transformation based on various antecedent basin conditions and temporal precipitation distribution,
- snow accumulation and melt,
- interception and infiltration, soil moisture accounting,
- evapotranspiration,
- regulated reservoir operation.

(3) The following input data will be needed for modeling the required hydrologic processes:

- stage-discharge data [hour+],
- precipitation and temperature data [hour+],
- potential evapotraspiration (PET) data [(day) month] (if not available then depending on the method used: relative humidity, sunshine duration, radiation, albedo, wind speed),
- generated sequences of meteorological data representing various scenarios of future climate (output from a weather generator),
- Digital Elevation Model (DEM), land use, soil types, and other basin physiographic data,
- channel and reservoir hydraulic data.

(4) The investment associated with hydrologic modeling encompasses the price of the hydrologic modeling software, the price of the technical support and costs related to the acquisition of the input data. The price of the hydrologic software may considerably vary, from free as-is products with usually limited technical support to commercial state-of-art software packages at the price of several thousand dollars. The technical support is likely to be needed especially when more sophisticated, distributed modeling packages are chosen, which may not be always included in the price, and thus can represent additional expenses (usually based on an annual subscription). Expenses related to the input data can be considerable especially when data of high-spatial resolution (such as DEM) are required.

A large number of existing hydrologic models (over 40) were reviewed in the preliminary screening process according to the four main criteria described above. Among them, a subset of 18 hydrologic models, which can be potentially used in the project, was identified. The 18 selected models are summarized in the following section.

IV. DESCRIPTION OF SELECTED MODELS

This section provides a brief summary of the 18 models selected an the first level of the selection process applied in the report. Some models do not fulfill all the fundamental criteria described in the previous section, but may be found attractive for solving partial project's tasks.

IV.1 Lumped hydrologic models

The selection of lumped hydrologic models is often attractive user's choice because of their simple structure, minimum data requirements, fast set up and calibration, and easy use. The representation of hydrologic processes in lumped hydrologic models is usually very simplified; however they can often lead to satisfactory results, especially if the interest is in the discharge prediction only. None of the three models selected in this report is capable of representing all hydrologic processes required by the project. Particularly reservoir routing is not simulated in the models, and some models also lack snowmelt or infiltration subroutines. However, they can effectively solve partial project's tasks such as modelling the potential climate change impact on river basin water balance or seasonal snow accumulation and melt. The following sections describe these models in more detail.

IV.1.1 IHACRES

The IHACRES (Identification of unit Hydrographs and Component flows from Rainfalls, Evaporation and Streamflow data) model is the result of collaboration between the Centre for Ecology and Hydrology (CEH) Wallingford, UK and the Australian National University (ANU), Canberra (Jakeman et al. 1990). IHACRES employs a transfer function/unit hydrograph (UH) approach to the lumped hydrologic modeling. The model allows the simulation of streamflow either continuously or for individual events from basins of various sizes using any data time step equal or greater than 1 min. The model has minimum input data requirements (rainfall, streamflow (for calibration), air temperature or evapotranspiration (optional) and basin size). Geographic descriptive data (topography, vegetation, soils) are not required. The model provides the following outputs: modeled streamflow and basin wetness index time series, unit hydrographs, hydrograph separation (dominant quick and slow flow components), and indicative uncertainties associated with the unit hydrograph parameters. The PC-IHACRES version of the model (Littlewood et al., 1997) includes a parameter optimization methodology. A new version IHACRES Classic+ will be available soon.

IV.1.2 SRM

The SRM (Snowmelt-Runoff Model) model was originally developed by Martinec (1975) at the Swiss Snow and Avalanche Research Institute (SSARI). The latest version is available from the Hydrology and Remote Sensing Laboratory, US Department of Agriculture, Agricultural Research Service (USDA-ARS). The model is designed to simulate and forecast daily streamflow in mountainous basins where snowmelt is a major runoff component. SRM is a simple degree-day model that requires input in the form of basin or zonal snow cover extent, temperature, precipitation, and the area-elevation curve of the basin. Additional parameters such as forested area, soil conditions, antecedent precipitation, and runoff can be also provided. Snowmelt in each zone is predicted from air temperature, any rainfall is added on, and the total new water is routed through a single store (USDA-ARS, 1998). The model also includes loss coefficients (at half-monthly intervals) applied to the snowmelt and rainfall terms. There is no provision for sub-basins or land cover types. A beta version of the SRM for Windows (WinSRM) is available from the USDA-ARS web site, which provides more robust support for climate change modeling, extensive enhancements to the model's graphical display capabilities, and an integrated approach to managing data sets for a given mountain basin (USDA-ARS, 2002).

IV.1.3 WATBAL

WATBAL is an integrated water balance model developed for climate change impact assessment of river basin runoff. The model evolved from a DOS based version known as CLIRUN (Kaczmarek, 1993) to the present MS Excel add-in form (Yates, 1994). There are two main components within the model; first is the water balance component that uses continuous functions to describe water movement into an out of a conceptualized basin. The second component is the calculation of potential evapotranspiration using the Priestly-Taylor radiation approach. The soil moisture balance is calculated using a differential equation and storage is lumped as a single bucket. Snowmelt component is used for computing an adjusted effective precipitation. The model can be applied using daily or larger time steps and for any basin size. The input data includes precipitation, runoff and potential evapotranspiration (which can be also calculated internally, using temperature, mean monthly relative humidity and sunshine duration data). Model outputs include PET, evapotranspiration, albedo, effective precipitation, surface and subsurface runoff. Some parameters of the model can be optimized.

IV.2 Semi-distributed hydrologic models

Several semi-distributed hydrologic models summarized in the following sections can be successfully used for simulating all hydrologic processes required by the project. The main advantage of semi-distributed models is that their structure is more physically-based than the structure of lumped models, and that they are less demanding on input data than fully distributed models.

IV.2.1 HBV-96

The HBV-model (Hydrologiska Byråns Vattenbalansavdelning) is a general-purpose hydrologic model developed at the Swedish Meteorological and Hydrologic Institute (SHMI). The HBV model is a standard forecasting tool in nearly 200 basins throughout Scandinavia, and has been applied in more than 40 countries worldwide. The model is designed to run on a daily time step (shorter time steps are available as an option) and to simulate river runoff in river basins of various sizes. The basin can be disaggregated into sub-basins, elevation zones, and land-cover types. Input data include precipitation, air temperature (if snow is present), monthly estimates of evapotranspiration, runoff (for calibration) and basin geographical information. The treatment of snow accumulation and melt in HBV is based on a simple accounting (degree-day) algorithm (SHMI, 2003). The existence and amount of snowfall is predicted using meteorological input data extrapolated to the mean elevation of each sub-area of the basin. A simple model based on bucket theory is used to represent soil moisture dynamics (Lindström et al, 1997). There is a provision for channel routing of runoff from tributary basins, using a modified Muskingum method. Outflow from lakes is usually specified by a stage-discharge rating curve but can be given by a lookup table to allow for power station operating rules. The HBV model can be linked with real time weather information and river monitoring systems.

IV.2.2 HEC-HMS

The US Army Corps of Engineers (US-ACE) Hydrologic Engineering Center HEC-HMS (Hydrologic Modeling System) model (successor to HEC-1) is designed to simulate both event and continuous simulation over long periods of time, and distributed runoff computation using grid-cell depiction of the watershed (US-ACE, 2002). HEC-HMS is comprised of a graphical user interface, integrated hydrologic analysis components, data storage and management capabilities, and graphics and reporting facilities (US-ACE, 2001). Infiltration losses can be simulated for event modeling by initial and constant, SCS curve, gridded SCS curve number, and Green & Ampt methods. The five-layer soil moisture accounting model can be used for continuous modeling of complex infiltration and evapotranspiration environments (US-ACE, 2000). Excess precipitation can be transformed into surface runoff by unit hydrograph methods

(Clark, ModClark, Snyder), and SCS technique. A variety of hydrologic routing methods are included for simulating flow in open channels (lag method, Muskingum method, modified Puls method, kinematic wave or Muskingum-Cunge method). Most parameters for methods included in subbasin and reach elements can be estimated automatically using the optimization manager. Version 3.0 (beta release scheduled for fall 2003), a new, substantial version written in Java will include additional reservoir capabilities for modeling interior flood zones, energy budget snow accumulation and melt, frequency curve generation, reservoir outlet structures, dam break, animated graphs of gridded precipitation and runoff results, plus user extensions (US-ACE, 2003).

IV.2.3 HFAM

HFAM (Hydrocomp Forecast and Analysis Modeling) is a semi-distributed model developed by Hydrocomp Inc. (Hydrocomp, 2002), based on the widely used Stanford Watershed Model (SWM) and the Hydrologic Simulation Program-Fortran (HSPF). The HFAM system consists of a hydrologic simulation model and a river-reservoir model. For the hydrologic simulation, the basin is divided into hydrologically homogeneous land segments. Each segment is simulated independently using local precipitation, evpotranspiration, temperature, solar radiation and wind. The hydrologic processes simulated include: snow accumulation and melt, interception of moisture by vegetation and other ground cover, overland flow and interflow, actual evapotranspiration and surface and shallow subsurface runoff. These processes are simulated on an hourly time step. The river-reservoir component simulates the operation of the reservoirs and routes the runoff from the land segments through the river channel network. Channel flow is routed using a modified version of the kinematic wave equation. Results include snow depth, runoff and actual evapotranspiration for each land segment, and flows throughout the river channel network. HFAM can be operated in three modes: short term forecasts, probabilistic (stochastic) medium term forecasts and long term analysis simulation mode.

IV.2.4 HSPF

The US Environmental Protection Agency (US-EPA) HSPF (Hydrologic Simulation Program-Fortran) program has its origin in the Stanford Watershed Model developed by Crawford and Linsley (1966). Hydrocomp, Inc. developed its present form. HSPF is a comprehensive, conceptual, continuous watershed simulation model designed to simulate all water quantity and quality processes that occur in a watershed, including sediment transport and movement of contaminants (Bicknell et al., 1997). It can reproduce spatial variability by dividing the basin in hydrologically homogeneous land segments and simulating runoff for each land segment independently. A segment of land can be modeled as pervious or impervious. In pervious land segments HSPF models the movement of water along three paths: overland flow, interflow and groundwater flow. Snow accumulation and melt, evaporation, precipitation and other fluxes are also represented. Routing is done using a modified version of the kinematic wave equation. HSPF includes an internal database management system for input and output.

IV.2.5 PRMS

The US Geological Survey (USGS) PRMS (Precipitation-Runoff Modeling System) model is a modular-design, deterministic modeling system developed to evaluate the impacts of various combinations of precipitation, climate, and land use on streamflow, sediment yields, and general basin hydrology (Leavesley et al., 1983). In PRMS a watershed can be divided into subunits based on basin characteristics (slope, aspect, elevation, vegetation type, soil type, land use, and precipitation distribution). Two levels of partitioning are available (USGS, 2000). The first divides the basin into homogeneous response units (HRU) based on the basin characteristics. The sum of the responses of all HRU's, weighted on a unit-area basis, produces the daily system response and streamflow for a basin. A second level of partitioning is available for storm hydrograph simulation. The watershed is conceptualized as a series of interconnected flow planes and channel segments. Surface runoff is routed over the flow planes into the channel segments; channel flow is routed through the watershed channel system. Output options include observed (if available) and predicted mean daily discharge, annual and monthly summaries of precipitation, interception, potential and actual evapotranspiration, and inflows and outflows of the ground water and subsurface reservoirs. Parameter-optimization and sensitivity analysis capabilities are provided to fit selected model parameters and evaluate their individual and joint effects on model output.

IV.2.6 SSARR

The SSARR (Streamflow Synthesis and Reservoir Regulation) model was developed by USGS North Pacific Division (USGS-NPD) to provide hydrologic simulations for the planning, design, and operation of water control works (USGS-NPD, 1991). The model consists of two modules, the snow computation module and the runoff analysis module. The runoff analysis module uses a single soil-moisture reservoir, which determines the percentage of available rainfall or snowmelt. For the snow computation module, SSARR computes snowmelt based on a temperature index approach or by a generalized snowmelt equation. The watershed can be divided into bands of equal elevation, on which snow accumulation and ablation, as well as soil moisture, are accounted for independently. The model time routine is flexible so that the time step may be set consistent with the data definition and project purpose. The hydraulic response of reservoirs, channel reaches, and backwater systems may be simulated individually or as components of a complex river system for study or real time operation. SSARR simulates all hydrologic processes required by the project. The original program runs on DOS and its input-output structure is very complex. SAR Consultants (SAR, 1999) have developed a GUI for the SSARR model and the product is sold under the name SSARRPC.

IV.2.7 SWAT

The USDA-ARS SWAT (Soil and Water Assessment Tool) program was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch et al., 2002b). The latest version SWAT2000 has a comprehensive structure that models basically all hydrologic processes in the watershed. Basins can be subdivided into subbasins to account for differences in soils, land use, crops, topography, weather, etc... Snow model allows the subbasin to be split into a set of elevation bands. Snow cover and snow melt are simulated separately for each elevation band. The model offers three options for estimating potential evapotranspiration: Hargreaves, Priestley-Taylor, and Penman-Monteith. Surface runoff volume is computed using a modification of the SCS curve number method or the Green & Ampt infiltration method. Flow is routed through the channel using a variable storage coefficient method or the Muskingum routing method (Neitsch et al., 2002a). The model also includes controlled reservoir operation, groundwater flow model and a weather generator that generates daily values (precipitation, air temperature, solar radiation, wind speed and relative humidity) from average monthly values. A new ArcView interface, AVSWAT2000 (Di Luzio et al., 2002) provides a user-friendly GUI.

IV.2.8 SWMM

The US-EPA Storm Water Management Model (SWMM) is a comprehensive dynamic hydrologic simulation model for analysis of quantity and quality problems associated with urban runoff (CHI, 2003). Both single-event and continuous simulation can be performed on urban basins. Modeller can simulate all aspects of the urban hydrologic and quality cycles, including rainfall, snowmelt, surface and subsurface runoff, flow routing through drainage network, storage and treatment. Flow routing can be performed in the Runoff, Transport and Extran blocks, in increasing order of sophistication. Extran block solves complete dynamic flow routing equations for accurate simulation of backwater, looped connections, surcharging, and pressure flow. The hydrologic simulation in the Runoff block uses the Horton or Green & Ampt equations where the data requirements include area, imperviousness, slope, roughness, width (a shape factor), depression storage, and infiltration values for either the Horton or Green & Ampt equations for up to 100 subbasins. The program is driven by precipitation for up to ten gages (distributed spatially), and evaporation. Basic SWMM output consists of hydrographs and pollutographs at any desired location in the drainage system. The model performs best in urbanized areas with impervious drainage. The model lacks GUI, but various vendors have developed user-friendly GUIs in the range of US$ 300-5,000 (OSU-CE, 2003): (PCSWMM - a menu-driven interface developed by Computational Hydraulics International ($400), XP-SWMM or Visual SWMM by XP Software ($5,000), the Danish Hydraulic Institute GUI for the Runoff and Extran Blocks, MIKE-SWMM ($5,000)). The Cincinnati Lab of EPA and Camp Dresser & McKee have completed Beta Test Version of SWMM5, a complete revision of SWMM that includes a graphical user interface (OSU-CE, 2003).

IV.2.9 TOPMODEL

TOPMODEL is a hydrologic model that bases its distributed predictions on an analysis of basin topography. The development of TOPMODEL was initiated by Michael Kirkby at the School of Geography, University of Leeds. The model was further developed by Keith Beven at the Lancaster University. Since 1974 there have been many variants of TOPMODEL but never a "definitive" version (Beven et al., 1995). The version described in this report was developed at the Lancaster University, runs on DOS, and its source codes (in FORTRAN) are in public domain. The model allows basins to be divided into a set of subbasins. Evaporation is estimated by using the Penman-Monteith method. Surface runoff is computed based on variable saturated areas. The subsurface flow is calculated using an exponential function of water content in the saturated zone. Channel routing and infiltration excess are calculated using the Beven and Kirkby method. The spatial component requires a high quality DEM without sinks. There is an extensive coverage of TOPMODEL in the scientific literature.

IV.3 Distributed hydrologic models

Distributed hydrologic models can provide the highest accuracy in the modeling of precipitation-runoff processes. Parameters of these models are fully spatially-varied at a given resolution and therefore require considerably more input data (often unavailable) than semi-distributed models. Most of the selected models described in the following sections can be used to address all project requirements.

IV.3.1 CASC2D

CASC2D was originally developed at the US Army Research Office (ARO) funded Center for Excellence in Geosciences at Colorado State University (Julien et al., 1995). CASC2D is a fully-unsteady, physically-based, distributed-parameter, raster (square-grid), two-dimensional, infiltration-excess (Hortonian) hydrologic model (Ogden, 1998). Major components of the model include: continuous soil-moisture accounting, rainfall interception, infiltration, surface and channel runoff routing, soil erosion and sediment transport. CASC2D can be used to simulate single events, or long periods of record at the users' discretion. A high-quality input data set is required for good model performance, and the quantity of input required is large. Continuous simulations require hourly input values of relevant meteorological and radiation variables, as well as Penman-Montieth evapotranspiration inputs (spatially-varied input maps of surface shortwave radiation albedo, vegetation height, canopy-average stomatal resistance, soil wilting point water content, and canopy shortwave radiation transmission coefficient). Also required are representative hourly estimates of air temperature, relative humidity, wind speed, and cloud cover. At present, there are two optional infiltration methods used in CASC2D (Ogden, 1998). The first is the traditional Green & Ampt approach. The use of this method requires input maps of soil porosity, saturated hydraulic conductivity, wetting-front suction head, and initial volumetric water content. The second method is an addition to the Green & Ampt approach that allows redistribution of soil water during inter-storm periods. Soil water redistribution requires two additional inputs, pore distribution index, and the soil water content at residual saturation. An explicit, two-dimensional, finite-difference, diffusive-wave scheme is used to route overland flow. Channel routing is performed using explicit, one-dimensional, finite-volume, diffusive-wave formulation that is suitable for simulations in headwater basins or using the Preissmann 4-point implicit scheme (Ogden, 1998). CASC2D can produce output maps of most hydrologic variables at user-specified intervals, including time-series maps of distributed soil surface moisture content surface water depth cumulative infiltrated depth channel flow depth channel and overland flow discharges overland flow erosion/deposition.

IV.3.2 CEQUEAU

CEQUEAU is a distributed water balance model developed at the INRS-ETE (Institut National de la Recherche Scientifique, Eau, Terre et Environnement). The model takes into account the spatial variability of basin physical characteristics by subdividing it into elementary representative areas, called "whole squares" (Morin, 2002). The characteristics required for each whole square are altitude and the percentage of forested area, lakes and marshes. Whole squares are further subdivided into "partial squares" according to subbasin divides, which allows to follow the formation and evolution of streamflow in time and for proper routing of runoff (St-

Hilaire et al., 2000). Data required for each partial square are direction of water flow and its percentage with respect to the subdivided whole square. The hydrologic model comprises two main functions. The first, production function quantifies the vertical movement of water. This function is modeled by a series of interconnected reservoirs representing different components of the hydrologic water balance (rainfall, snow accumulation and melt, evapotranspiration, water in the unsaturated and saturated zones, and lakes and marshes). The production function calculates volumes of water in each whole square. The second, transfer function then routes these volumes downstream from one square to the other. The water volume available in a partial square is obtained by multiplying the volume produced on a whole square by the percentage of area occupied by the partial square. This volume is added to volumes entering a given element from other partial square(s) located directly upstream. The routing process is repeated from one element to the next up to the exit of the watershed. The routing of each partial square is related to the hydraulic characteristics, and to the storage capacity of the drainage network. The adjustment of model parameters is done by trials and errors or by optimization. Temporal data required by CEQUEAU include maximum and minimum air temperatures, liquid and solid precipitation, and observed streamflow for the calibration period. The model provides outputs for daily rain, mean daily temperature, snow accumulation, mean daily snowmelt, daily evaporation, and modeled discharge. The CEQUEAU model allows real time streamflow forecasting for short and mid-term with or without updating. The model was applied in sixty watersheds in the province of Québec ranging from 1 to 100,000 km^2. Some applications involved the determination of probable maximum floods (PMF). CEQUEAU model is presently used on a regular basis for real time flow forecasting by some institutions in the Province of Québec (Morin, 2002).

IV.3.3 GAWSER/GRIFFS

GAWSER (Guelph All Weather Sequential Event Runoff) model was developed to predict streamflow from rainfall and snowmelt precipitation events. The model was applied in the Grand River Watershed, where gradually evolved into real-time flood forecast model GRIFFS (Grand River Integrated Flood Forecasting System). The Grand River Conservation Authority (GRCA) uses GRIFFS to make flood forecasts and test reservoir operations during floods, to estimate design flows for floodplain mapping and to test the impact of land use changes on streamflow. GRIFFS is capable of modeling single or multiple events and has provisions for recovery between events. The model includes temperature based snowmelt routines, distributed snowpack model, modified Green & Ampt infiltration model, Muskingum-Cunge channel routing, overland flow area per time curve routing and sub-surface flow routing (Boyd et al., 2000). The model provides comparison plots and statistics for observed and simulated flows at streamflow locations, detailed output of runoff calculations, a forecast summary which includes the forecast peak flow and time of peak flow at selected points of interest, reservoir storage forecast peak and time of peak, forecast peak inflows to reservoirs, automatic conversion of forecast flows to forecast levels for specified points of interest, summary table of when flooding is expected to start and stop at a given point of interest, summary table of parameter setting and full water balance. The model has shown excellent results on the Grand River Watershed. Future improvement to this model will focus on incorporation of real-time weather radar and numerical weather model precipitation information and integration with GIS (Boyd, et al., 2000).

IV.3.4 HYDROTEL

The INRS-ETE's HYDROTEL is a spatially distributed hydrologic model with physical bases specifically developed to facilitate the use of remote sensing and geographical information system data (Fortin, 2000a). The program has a modular structure allowing easy addition or modification of algorithms. The complete drainage structure of a watershed is obtained with PHYSITEL, a module designed specifically to prepare the watershed database for HYDROTEL. The spatial variability is in HYDROTEL modeled using relatively homogeneous hydrologic units (RHHU). Daily snowmelt and accumulation are estimated by a modified degree-day method in which the energy budget at the snow-air interface is estimated by the degree-day approach but that within the pack by a more physical approach. Four equations are available to estimate potential evapotranspiration (Fortin et al., 2000a): Thornthwaite, Linacre, Penman-Monteith and Priestley-Taylor. The vertical water budget is simulated by the vertical algorithm of the CEQUEAU model or by a new algorithm more suited to remote sensing and GIS information (BV3C method). A kinematic wave approach is used to estimate downward flow from cell to cell, whereas river routing is simulated with the kinematic or diffusive wave equations. HYDROTEL has only few parameters that are influenced by the change in time step. This allows the model to be first calibrated using daily data, and then the calibration obtained with daily data may be adjusted for simulations with shorter time steps. HYDROTEL has been applied in watersheds located in Québec, Ontario and British-Colombia (Fortin et al., 2000b).

IV.3.5 MIKE11/SHE

MIKE11 is a commercial engineering software package developed at the Danish Hydraulic Institute (DHI). The model is a dynamic, one-dimensional modeling tool based on an integrated modular structure with a variety of basic modules and add-on modules, each simulating certain phenomena in river systems. MIKE11 includes basic modules for rainfall-runoff, hydrodynamics, advection-dispersion, water quality and sediment transport. The rainfall-runoff module contains three different models that can be used to estimate basin runoff (DHI, 2000a): 1) the continuous simulation (NAM) module, a lumped, conceptual rainfall-runoff model that simulates overland flow, interflow and baseflow; 2) the UHM module that simulates the runoff from single storm events by the use of the unit hydrograph technique; 3) SMAP, a monthly soil moisture accounting model. A global optimization routine called the Shuffled Complex Evolution algorithm optimizes the model parameters. The Hydrodynamic module uses an implicit, finite difference computation method for modeling of unsteady flows in rivers and estuaries. Other extensions are the Dam break module, the Structure Operation module or the MIKE11 GIS, an ArcView-based application that provides both a spatial data and visual representation of MIKE11 various outputs. MIKE11 can be coupled with MIKESHE, integrated, physically based, fully distributed, modular, dynamic modelling system, the DHI version of the original SHI (Systeme Hydrologique Europeen) program developed through a joint project of CEH Wallingford, Danish Hydraulics Institute and SOGREAH (France). The model is applicable on spatial scales ranging from single soil profiles (for infiltration studies) to regional watershed studies. MIKESHE includes all of the processes in the land phase of the hydrologic cycle: precipitation (rain or snow), evapotranspiration, interception, overland sheet flow, channel flow, unsaturated sub-surface flow and saturated groundwater flow. Evapotranspiration is calculated using the Kristensen and Jensen method. MIKESHE's overland-flow component includes a 2D finite difference diffusive wave approach using the same 2D mesh as the groundwater component. MIKESHE includes a traditional 2D or 3D finite-difference groundwater model. There are three options in MIKESHE for calculating vertical flow in the unsaturated zone: the full Richards equation, a simplified gravity flow procedure, and a simple two-layer water balance method for shallow water tables (DHI, 2000b). MIKE11/SHE product is the most widely used hydraulic modeling system in the world and has been approved for use by regulatory authorities in many countries including USA, Australia and UK. (DHI, 2003).

IV.3.6 WATFLOOD

WATFLOOD is a distributed hydrologic model for real time flood forecasting and continuous simulation developed by Nicholas Kouwen at the University of Waterloo. The emphasis of the WATFLOOD system is on making optimal use of remotely sensed data. Radar rainfall data, LANDSAT or SPOT land use and/or land cover data can be directly incorporated in the hydrologic modeling. WATFLOOD uses Grouped Response Units (GRU), in which process parameters are tied to land cover. GRUs lead to universal parameter set because parameters are associated with land cover and not watersheds (Kouwen, 2001). The combination of GRU's and grids make the effective resolution much greater than the grid size used. WATFLOOD uses the Hargreaves, Priestley-Taylor or climatic evaporation methods. Snow accumulation and melt is modeled using a temperature index model or a Radiation-Temperature Index Algorithm. The Philip formula is chosen for representing physical aspects of infiltration process. Other features include reservoir operating rules, automatic soil moisture initialization for flood forecasting, grid shifting for ensemble forecasting, and Hooke & Jeeves pattern search optimization.

V. COMPARISON OF SELECTED MODELS

This section attempts to compare the selected hydrologic models briefly introduced in the previous sections according to various evaluation criteria. Some criteria are informative, other are ranked and included in the evaluation process. Lumped, semi-distributed and fully-distributed models are compared separately, since they reflect different approaches to hydrologic modeling. Lumped models are summarized in Table 1, semi-distributed models in Table 2 and distributed models in Table 3. All three tables describe the selected models according to:

- Temporal scale; the time step used in the model [min(+/-), hr(+/-), day(+/-), month(+/-), flexible] (where "+" means given and larger time step, and "-" means given and shorter time step). Rank: [0-2]; models with flexible time step receive the highest rank 2, models with limited time step but at least partially applicable in the project (e.g. for event or continuous simulation) get 1, and models with time steps that cannot be applied in the project get 0 (not used).
- Spatial scale; for what basin size is the model developed or recommended to be used [small (urban areas), medium (up to 1000 km^2), large (>1000 km^2), flexible size]. Rank: [0-2]; 2 for flexible size, 1 for models with partially applicable spatial scale, and 0 for inapplicable models (not used).
- Processes modeled; this section lists all hydrologic processes that are important for the project (event-simulation, continuous simulation, snow accumulation and melt, interception & infiltration, evapotranspiration and reservoir routing). Rank: [0-12] (0-2 for each process); where 0 is used if a given process is not modeled at all, 1 if partially modeled (such as unregulated reservoir routing or simplified infiltration modeling) and 2 if a process is completely modeled.

- Cost; price of the model [US$ or CAD$]. Rank: [0-2]; 0 for expensive models (> US$ 1,000), 1 for models with price ≤ US$ 1,000, and 2 for models in public domain. Expenses related to technical support are also considered here.
- Set-up time; approximate time needed to set the model into operational use [short, medium, long]. Rank: [0-2]; 1-low, 2-medium, and 0-high.
- Expertise; what scientific expertise is required to use the model adequately [low, medium, high]. Rank: [0-2]; 1-low, 2-medium, and 0-high.
- Technical support; support available for setting up the model, calibration and use [-]. Rank: [0-2]; 0 if no support is available, 1 for limited support and 2 for full support.
- Documentation; what documentation is available about the model, such as user's guides, reference manuals, web pages, newsletters, etc… [bad, medium, good]. Rank: [0-2]; 0-bad, 1-medium, and 2-good.
- Ease-of-use; describes computer-related user-friendliness of the model, taking into account GUI, input-output (I/O) operations, and visualization options [easy, medium, difficult]. Scientific aspects are considered in the entry "Expertise". Rank: [0-2]; 2-easy, 1-medium, and 0-difficult.
- OS; computer operation system required for the model [UNIX, DOS, Mac, Win 95, 98, Me, 2000, XP]. Rank: [0-2]; 2 for Windows based applications, 1 for DOS applications, and 0 for other operation systems.
- Advantages and disadvantages; summarizes pros and cons of a given model. Rank: [-].
- References; lists the key reference(s) to the model in the literature. Rank: [-].
- Additional comments; any additional information worth mentioning. Rank: [-].
- Total score; gives the sum of all ranked criteria [0-30].

Not known information is in Tables 1, 2 and 3 denoted as "Not known". Not known items received during the ranking process the median value, in order to minimize any potential errors resulting from misclassification.

As can be seen from Table 1, the IHACRES model has limited application for the assessment of the impact of climate change on the river runoff in the Upper Thames River basin because snowmelt and infiltration are not accounted for in the model. On the other hand, IHACRES can be used in the project for the derivation of unit hydrographs (as inputs to more advanced models), data screening, and preliminary single-event simulations. Infiltration and evapotranspiration are also not modeled in the SRM model, and therefore this model should be only used for evaluating the potential effect of climate change on the seasonal snow accumulation and snow-induced runoff. There is also no provision for single-event simulations in the SRM model. The WATBAL model lacks flow and reservoir routing and infiltration subroutines. The model can be applied for preliminary assessment of the climate change impacts on hydrologic regime and water balance using monthly time step.

Table 2 summarizes the selected semi-distributed models. The HBV model can potentially reproduce all main hydrologic processes with the accuracy required by the project. Questionable remain the performance of the model on time steps shorter than one day (event-simulations), simplified soil moisture dynamics and controlled reservoir operation. The only disadvantage of the current version of HEC-HMS with respect to the project is that snow accumulation and melt is not included in the model. Reservoir routing is based on the modified Puls technique, which may not be applicable in cases where reservoirs are operated with controlled outfow. However the HEC-ResSim package can be used for modelling controlled outflow instead. Version 3.0 will include both snow and improved reservoir operation modules.

Table 1. Selected lumped models.

Model / criterion	IHACRES [1]	SRM[2]	WATBAL[3]
Temporal scale	Flexible (Min+)	Day	Day+
Spatial scale	Flexible	Flexible	Flexible
Processes modeled: Event-simulation	Yes	No	No
Continuous simulation	Yes	Yes	Yes
Snow acc. and melt	No	Yes	Yes
Interception & Infiltration	No	No	No
Evapotranspiration	Yes*	No	Yes
Reservoir routing	No	No	No
Cost	Public Domain	Public Domain	Public Domain
Set-up time [Short/Medium/Long]	Short	Medium	Short
Expertise [Low/Medium/High]	Low	Medium	Low
Technical support	Possibly from the author	Workshops in the past Message Board	No support
Documentation [Bad/Medium/Good]	Good	Good	Good
Ease of use [Easy/Medium/Difficult]	Easy	Medium	Easy
OS	Win95+	DOS Win 95+*	Win 95+ MS Excel 5.0+ Add-in
Advantages	Easy to use Low data requirements Both event and continuous simulations	Latest version allows to model the effect of climate change on the runoff regime for the entire hydrologic year	Easy to use Developed for climate change impact studies Some parameters can be optimized
Disadvantages	Snowmelt not modeled * Cannot be internally computed (temperature can be also used for estimating evapotranspiration effects)	Developed for basins with dominant snowmelt runoff No event simulations	No event simulations Empirical parameters
References	Littlewood et al. (1997)	USDA-ARS (1998)	Yates (1994)
Comments	Could not install help files Next-generation IHACRES 'Classic Plus' software available soon	Applied in 25 countries *WinSRM Beta available for testing from USDA-ARS	Simple water balance model VB source code available
Total score [0-30]	20	19	19

(1) IHACRES (Identification of unit Hydrographs and Component flows from Rainfalls, Evaporation and Streamflow data), Centre for Ecology and Hydrology, Wallingford and the Integrated Catchment Assessment and Management Centre (ICAM), Australian National University, Canberra.

(2) SRM (Snowmelt Runoff Model), US Department of Agriculture Agricultural Research Service (USDA-ARS), Hydrology Laboratory.

(3) WATBAL (Water Balance Model), International Institute for Applied Systems Analysis (IIASA).

Table 2. Selected semi-distributed models.

Model / criterion	HBV-96[1]	HEC-HMS[2]	HFAM[3]	HSPF[4]	PRMS[5]	SSARR[6] /SSARRPC	SWAT[7] /AVSWAT	SWMM[8]	TOPMODEL[9]
Temporal scale	Day-	Flexible	Day-	Day-	Day-	Flexible	Day+	Hr-	Day-
Spatial scale	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Medium+	Small	Flexible
Processes modeled: Event-simulation	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Continuous simulation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Snow acc. and melt	Yes	No*	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Interception & Infiltration	Yes*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Evapotranspiration	Yes*	Yes**	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reservoir routing	Yes	Unregulated*	Yes	Yes	Not known	Yes	Yes	Unregulated only?	Not known
Cost	Not known	Public Domain	US$ 595 Acad US $95	Public Domain	Public Domain	Public Domain /US$495	Public Domain	Public Domain /GUI US$ 500-5000 (Acad less)*	Public Domain
Set-up time [Short/Medium/Long]	Medium	Medium	Medium	Long	Long	Long	Long	Long	Long
Expertise [Low/Medium/High]	Medium	Medium	Medium	High	High	High	High	High	Medium
Technical support	Provided by the SHMI's International Consulting Services	Annual subscription service for Corps Fee-for-service support from third-party vendors	Workshop for US$ 1295 (includes HFAM CD)*	No support (Hydrocomp Inc. used to provide training in the past)	No support (USGS used to provide training in the past)	No USGS support /SAR Consultants provide fee-for-service support	List server Development team	From third-party vendors	No support
Documentation [Bad/Medium/Good]	Not known	Good	Not known	Good	Not known*	Good /Not known	Good	Good	Good
Ease of use [Easy/Medium/Difficult]	Medium	Medium	Medium	Difficult	Difficult	Difficult	Difficult	Difficult	Difficult
OS	Win 95, NT	Win 95, 98, 2000	Win 95, 98, NT	DOS, UNIX	DOS, UNIX	DOS	DOS /ArcView	DOS, Win*	DOS, Win 3.1+
Advantages	All hydrologic processes modeled Fairly low data requirements	State-of-art product in public domain Input data already in HEC format Compatible with HEC-GEOHMS HEC-ResSim and other US-ACE packages Flexible structure	All hydrologic processes modeled Professional tool	All hydrologic processes modeled HEC-DSS compatibility HSPEXP- Expert system for calibration of HSPF Public domain	Parameter optimization and sensitivity analysis capabilities	All hydrologic processes modeled /HEC-DSS compatibility	Comprehensive model structure AVSWAT GUI Public domain	All hydrologic processes modeled GUI (third-party vendors): PCSWMM Visual SWMM MIKE-SWMM	Broad coverage in research papers Newsletters Mailing list Public domain
Disadvantages	Designed for daily time step *Simplified soil moisture dynamics Limited information available	Snow accumulation and melt, reservoir outlet structures, and dam break are under development but not yet incorporated* ** Cannot be internally computed	Extensive data demand Limited information available	DOS I/O operations Extensive data demand No support	DOS I/O operations No support Limited available information	I/O operations Extensive data demand /1999 version still uses DOS-batch programs /Limited available information	No event simulations Extensive data demand /Limited available information	URBAN areas oriented (but not exclusively) Small basins Time step not flexible	No final version Win version simplified No support

Table 2. (Cont'd)

References	Lindström et al. (1997) SHMI (2003)	US-ACE (2000, 2001, 2002)	Hydrocomp (2002)	Bicknell et al. (1997)	Leavesley et al. (1983)	USGS-NPD (1991) /SAR Consultants (1999)	Neitsch et al. (2002a, b) /De Luzio et al. (2002)	Huber and Dickinson (1988)	Beven et al. (1997)
Comments	Standard forecasting tool in Sweden Applied in 40+ countries worldwide	* New, revised version 3.0 coming in fall 2003 will include these features	GUI for HSPF DEMO available May 2002 last web update *No new workshops scheduled	Evolved into HFAM which has GUI	*Printed documentation can be ordered from USGS FORTRAN source codes available	FORTRAN source codes available	Extensive documentation	SWMM Beta 5.0 available for testing (GUI, but no snowmelt and groundwater)	FORTRAN source codes available Many applications worldwide
Total score	24	25 (*28)	25	19	17	21	19	20	21

(1) HBV-96 (Hydrologiska Byråns Vattenbalansavdelning), Swedish Meteorological and Hydrologic Institute (SHMI).
(2) HEC-HMS (Hydrologic Engineering Center Hydrologic Modeling System), US Army Corps of Engineers (US-ACE).
(3) HFAM (Hydrocomp Forecast and Analysis Modeling), Hydrocomp Inc.
(4) HSPF (Hydrologic Simulation Program - Fortran), US Environmental Protection Agency (US-EPA).
(5) PRMS (Precipitation-Runoff Modeling System), US Geological Survey (USGS).
(6) SSARR (Streamflow Synthesis and Reservoir Regulation Model), US Geological Survey (USGS).
(7) SWAT (Soil and Water Assessment Tool), US Department of Agriculture Agricultural Research Service (USDA-ARS).
(8) SWMM (The Storm Water Management Model), US Environmental Protection Agency (US-EPA).
(9) TOPMODEL, Lancaster University.

Table 3. Selected distributed models

Model / criterion	CASC2D[1]	CEQUEAU[2]	GAWSER/GRIFFS[3]	HYDROTEL[4]	MIKE11/SHE[5]	WATFLOOD[6]
Temporal scale	Hr-	Day-	Day-	Flexible	Flexible	Flexible
Spatial scale	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible
Processes modeled: Event-simulation	Yes	Yes*	Yes	Yes	Yes	Yes*
Continuous simulation	Yes	Yes	Yes	Yes	Yes	Yes
Snow acc. and melt	No	Yes	Yes	Yes	Yes	Yes
Interception & Infiltration	Yes	Yes	Yes	Yes	Yes	Yes
Evapotranspiration	Yes	Yes	Yes	Yes	Yes	Yes
Reservoir routing	No	Unregulated only?	Yes	Yes	Yes	Yes
Cost	Public Domain* /WMS US$ 2,000-4,600	Likely free for academic research	Not known	Not known	US$10,000 (min configuration) 80% off acad offer	CAD$ 2,000 Academic ≈ CAD$ 300
Set-up time [Short/Medium/Long]	Long	Long	Long	Long	Long	Medium
Expertise [Low/Medium/High]	High	High	High	High	High	High
Technical support	No support for non-Corps users /** Free from EMS to all licence holders of WMS	From the author and other users at INRS	Possibly from the author/GRCA but details not known	From the author and other users at INRS	DHI Software Support Centres Training courses	From the author and UW users
Documentation [Bad/Medium/Good]	Good	Good	Not known	Good	Good	Good
Ease of use [Easy/Medium/Difficult]	Difficult	Medium	Not known	Medium	Medium	Medium
OS	DOS, Win**	Win 3.1+	Not known	Win 95+	Win 95+	Win 95+
Advantages	** The Watershed Modeling System (WMS) GUI for CASC2D developed by the Engineering Computer Graphics Laboratory at Brigham Young University	Distributed water balance model Real time flow forecasting	All hydrologic processes modeled Developed for hydrologically similar basin	All hydrologic processes modeled Integrated program (PHYSITEL) for deriving distributed inputs	All hydrologic processes modeled State-of-art product Highly flexible, various add-on modules available	All hydrologic processes modeled Good support expected Reasonable data demand
Disadvantages	Snowmelt and reservoir modelling not included Extensive data requirements Experienced users only Time step not flexible	Not suited for event simulations Input data structure * Simplified channel routing	Likely customized for specific GRCA needs Limited information available	Technical support likely needed	Price Technical support likely needed Annual subscriptions	A step behind commercial products Obsolete GUI * Simplified channel routing
References	Ogden (1998) Julien et al. (1995)	Morin (2002)	Schroeter & Associates (1996)	Fortin et al. (2001a, 2001b)	DHI (2000a,b)	Kouwen (2001)
Comments	* Permission from the US-ACE required GRASS ASCII data file formats	Applied in 60+ basins in the province of Québec	The model has shown excellent results on the Grand River basin	Applied in several Canadian provinces	Not known if the Software Maintenance Agreement is included in the price	WATFLOOD LITE available for student use
Total score	17	21	20	24	23	23

[1] CASC2D, Department of Civil & Environmental Engineering, The University of Connecticut (originally at Colorado State University).
[2] CEQUEAU, Institut National de la Recherche Scientifique, Eau, Terre et Environnement (INRS-ETE).
[3] GAWSER (Guelph All Weather Sequential Events Runoff model), University of Guelph; GRIFFS (Grand River Integrated Flood Forecasting System), The Grand River Conservation Authority (GRCA).
[4] HYDROTEL, Institut National de la Recherche Scientifique, Eau, Terre et Environnement (INRS-ETE).
[5] MIKE11/SHE, Danish Hydraulic Institute (DHI) Water and Environment.
[6] WATFLOOD, University of Waterloo.

The only concerns related to the Hydrocomp's HFAM model is its rather extensive data demand and limited, but likely needed technical support. A major disadvantage of HSPF is that it has no graphical user interface (runs on DOS), extensive data demand, and no technical support. The more user-friendly HFAM that builds on HSPF would be therefore a better choice. Similarly to HSPF, the main disadvantages of the PRMS and SSARR models are extensive input data demand, no technical support, and a lack of user-friendly GUI, thus difficult I/O operations. SAR Consultants (SAR, 1999) developed a new version of SSARR (SSARRPC), but the program still uses DOS-batch programs. The model is therefore still likely difficult to use. Another model in this category, SWAT, is a continuous, long-term yield model, and is not designed to simulate detailed, single-event flood routing. Therefore it can only be used partially in the project for continuous simulations using daily or longer time steps. The main limitation of the SWMM model is that it is designed for small and predominantly urban watersheds. The model can be used in the project for simulating runoff from subbasins or smaller urban areas that are of special interest. There is no final version and only a limited support available for the TOPMODEL program (mostly from other users). Setting up TOPMODEL FORTRAN codes, model operation as well as the pre and post data processing is likely to be difficult.

Table 3 compares selected distributed models. The first model in this category, CASC2D requires a highly experienced user, and US-ACE does not currently support non-Corps users. Moreover, the current version lacks snowmelt and reservoir routing subroutines and therefore will not be the best choice for this project. The distributed water balance model CEQUEAU can be used for continuous precipitation-runoff simulations and real time flow forecasting. The model is less suitable for single event simulations (simplified river routing). The HYDROTEL model can simulate all required components of the hydrologic cycle. An integrated program (PHYSITEL) is included in the model for deriving distributed basin inputs. Set up time and expertise is expected to be high for this model. GAWSER/GRIFFS model has been developed for hydrologically similar, neighbouring basin (Grand River), and thus it will likely produce good results on the Upper Thames as well. On the other hand, the model structure may reflect some customizations and specific GRCA data and I/O operation needs, and will possibly require extensive GRCA training and support. The MIKE11/SHE package is top-ranked, state-of-art product in its category. The price of the model, additional add-on modules and technical support may represent an important factor to consider in this project. The extent of WATFLOOD in terms of included hydrologic processes is comparable with other products on the market. The WATFLOOD storage routing technique makes the model less suitable for single event modeling from small river basins (subbasins). Its VB5 GUI is a step behind the current trend, but good technical support can be expected.

Figure 1 shows the total scores obtained for all models grouped according to the three types of models. Black bars depict the highest scores for each type.

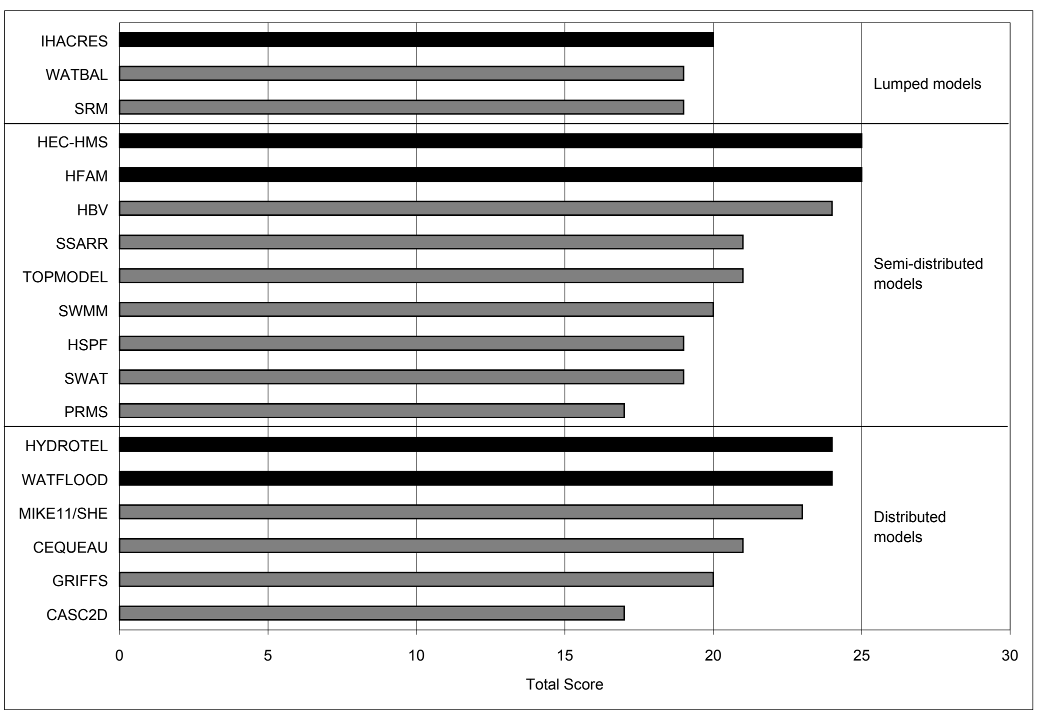

Figure 1. Selected hydrologic models according to the total score.

Among the selected lumped models the IHACRES model slightly leads with 20 points. The main advantage of this model is that it can be used for simulating both event-based and continuous simulations. The model is also flexible in terms of basin size and input data time step. IHACRES can be easily set-up and calibrated, does not require experienced users and has good documentation. The new IHACRES version will include more modeling features, which will likely further increase its score. The model is in public domain.

The HEC-HMS and HFAM models equally scored 25 points. Both models are flexible in temporal and spatial scales, and require medium set-up time and expertise. The structure of HFAM includes all required hydrologic processes, but its technical documentation is not known, the Hydrocomp web site has not been updated since May 2002, and no new workshops are scheduled, which may suggest that this model is no longer supported. The price of HFAM is US$ 595 with discounts available for academic institutions. The new HEC-HMS version will bring substantial improvements to the model structure, including snow accumulation and melt, frequency curve generation, reservoir outlet structures, dam break, and user extensions. With these features the new HEC-HMS would gain 28 points, thus clearly leading among the semi-distributed models. HEC-HMS is in public domain.

Regarding the selected distributed models, the HYDROTEL and WATFLOOD models seem to be the best choices for this project. Both models were developed in Canada, have impressive structure that can reproduce all hydrologic processes required by the project, and good technical support. An academic price is available for WATFLOOD (around CAD$ 200-300) and is also expected to be available for HYDROTEL. Both models have the capacity to lead to excellent, spatially highly detailed results.

VI. CONCLUSIONS AND RECOMMENDATIONS

None of the selected lumped models can be used alone for modeling the hydrologic components required by the project objectives. This implies that if a lumped modeling approach is chosen, then set-up and calibration of another model will be necessary, which may not be within the time constraints of the project. Among the lumped models IHACRES gained the highest score, and if a lumped hydrologic modeling will be required at some stage of the project, then this model should be used.

With respect to the project, a more attractive choice would be to opt for a semi-distributed model, which will be a good compromise between generally high simplification of the governing hydrologic processes used in lumped models, and extensive data requirements of distributed models. The current version of the HEC-HMS model is a highly flexible package (7 infiltration methods, 6 streamflow routing, 3 baseflow and 3 reservoir routing methods) in public domain, with a very sophisticated GUI comparable with GUIs of expensive commercial packages. The model uses HEC-DSS data format, which is the format used by the Upper Thames River Conservation Authority (UTRCA). Its modular structure allows taking advantage of other HEC products, such as HEC-ResSim for regulated reservoir simulation. The only missing component is snowmelt, but this can be programmed or added from existing subroutines. A new HEC-HMS Version 3.0 will cover both reservoir operation and snowmelt (Beta should appear in the Fall 2003), and would be an excellent choice for this project (worth waiting for).

Finally, the WATFLOOD model seems to be the best choice among the selected distributed models. The key advantages of WATFLOOD are less data demanding flow routing technique and good support/training available at the University of Waterloo. The model is a strong candidate for the project in the case that the new HEC-HMS version is not available.

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VIII. ABBREVIATIONS

ANU	Australian National University
ARO	(United States) Army Research Office
CEH	Centre for Ecology and Hydrology
CFCAS	Canadian Foundation for Climatic and Atmospheric Sciences
DEM	Digital Elevation Model
DHI	Danish Hydraulic Institute
GAWSER	Guelph All Weather Sequential Event Runoff
GIS	Geographic Information System
GRCA	Grand River Conservation Authority
GRIFFS	Grand River Integrated Flood Forecasting System
GRU	Grouped Response Units
GUI	Graphical User Interface
HBV	Hydrologiska Byråns Vattenbalansavdelning
HFAM	Hydrocomp Forecast and Analysis Modeling
HMS	Hydrologic Modeling System
HRU	Homogeneous Response Units
HSPF	Hydrologic Simulation Program Fortran
IHACRES	Identification of unit Hydrographs and Component flows from Rainfalls, Evaporation and Streamflow data
INRS-ETE	Institut National de la Recherche Scientifique, Eau, Terre et Environnement
KW	Kinematic Wave
OS	(computer) Operation System
OSU-CE	Oregon State University Civil Engineering
PD	Probability Distributed
PET	Potential EvapoTranspiration
PMF	Probable Maximum Flood
PRMS	Precipitation Runoff Modeling System
RHHU	Relatively Homogeneous Hydrologic Unit
SHI	Systeme Hydrologique Europeen
SHMI	Swedish Meteorological and Hydrologic Institute
SRM	Snowmelt Runoff Model
SSARI	Swiss Snow and Avalanche Research Institute
SSARR	Streamflow Synthesis and Reservoir Regulation
SWAT	Soil and Water Assessment Tool
SWM	Stanford Watershed Model
SWMM	Storm Water Management Model
UH	Unit Hydrograph
US-ACE	United States Army Corps of Engineers
USDA-ARS	United States Department of Agriculture, Agricultural Research Service
US-EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
USGS-NPD	United States Geological Survey North Pacific Division
UTRCA	Upper Thames River Conservation Authority