4.0 GAWSER Model

A comprehensive hydrologic model is required to quantify and characterize the key hydrologic components within a watershed. Although any model is a simplification of the movement of water through the environment, the appropriate model should be able to make valid inferences regarding the key hydrologic processes within a watershed. In order to provide a general overview of the surface water flow component of the hydrologic cycle, a basic description of the key physical processes is given below.

4.1 SUMMARY OF THE HYDROLOGIC CYCLE

The hydrologic cycle refers to the movement of water through the earth-atmosphere system. This cycle is initiated with the collection of water vapour by evaporation and transpiration from water and land surfaces and transpiration from vegetation, followed by the release of water when it condenses in the atmosphere (clouds) and is returned to the earth by precipitation. At the earth's surface, the precipitation is stored on the surface (e.g., rivers, lakes, oceans) or below the surface (groundwater) or is evaporated or transpired to repeat the next cycle.

The hydrologic cycle begins with rain or snow (precipitation) falling to the ground. The amount and rate of precipitation that arrives at the ground surface is governed by the prevailing weather system that generated the precipitation on a regional scale. At the more localized scale, topography and land use cover influence the actual precipitation amounts arriving at the ground surface.

Water (as rain, snowmelt or both) either runs off across the ground surface directly to a surface watercourse or infiltrates (percolates) into the ground. The amount of water that actually infiltrates is controlled by the rate of precipitation input (rainfall or snowmelt), soil type (e.g., clay, silt, sand or gravel), ground surface conditions (e.g., frozen, cracking) and vegetative cover (e.g., pasture, forests). Water infiltrating the ground may follow a number of processes including; remaining in soil water storage under dry conditions, return to the atmosphere by evapotranspiration, discharge relatively quickly to surface water through interflow, percolate into deeper soils and recharge groundwater. In some areas (e.g., hummocky ground), the surface topography has created large depressions, which require up to several metres of water to pond before overland flow occurs. Consequently, water in these depressions either percolates downward and contributes to groundwater and subsurface storage or evaporates back to the atmosphere.

Runoff water collects in stream channels leading to larger channels or discharge to ponds, wetlands or lakes. While in these ponds or lakes, a portion of this water returns to the atmosphere by evaporation, or it may percolate into the ground, or spill to downstream channels. The travel time of flow in these stream channels is governed by the length, slope, roughness and cross-sectional shape of these channels. If the flow is high and fast enough, water may overtop the channel banks, flooding the adjacent land area.

Anywhere along the length of these stream channels, discharge from groundwater storage (either regional, localized, or interflow) can contribute to the flow in the channel. These groundwater contributions to streamflow are governed by the surrounding topography, surficial geology and bedrock geology.

4.2 MODEL SELECTION

As described in Section 1.4, the GRCA has developed a continuous GAWSER to simulate watershed hydrology. The current hydrologic model was originally constructed for flood forecasting purposes in the late 1980s, and has been in a continual improvement process ever since. The event based model was converted to continuous mode in the late 1990's at which time a substantial calibration/verification exercise was carried out. More recently, the GAWSER model was revisited based on initial feedback from the three-dimensional groundwater flow model. The current GAWSER model represents in excess of 15 years of continuous improvement, and has been successfully tested in hundreds of real-time flood forecasting events.

The Guelph All-Weather Storm-Event Runoff (GAWSER) model (Schroeter and Associates, 2004) is a deterministic storm-event hydrologic model which can be used to simulate major hydrologic processes, or streamflow hydrographs resulting from precipitation inputs for the purpose of planning, design or evaluating the effects of physical changes in the drainage basin. GAWSER has been applied widely in Ontario for planning, design, real-time flood forecasting, and evaluating the effects of physical changes in the drainage basin (Schroeter & Associates, 2004). Precipitation inputs can be defined in terms of rainfall, snowmelt or a combination of both. For simulation, drainage basins can be divided into a series of linked elements representing watersheds, channels and reservoirs. The physical effects of each element are simulated using efficient numerical algorithms representing tested hydrologic models.

The snowmelt sub-model uses a temperature index approach to calculate melt and refreeze, simulates compaction and computes the liquid water holding capacity of the snowpack. Spatially variable infiltration at the soil surface, percolation rates within the soil and overland runoff estimates are accounted for by considering a watershed comprising impervious and pervious areas. Each pervious zone is modelled as two soil layers, and the Green-Ampt equation is used for infiltration calculations. Overland runoff routing is accomplished by the area/time versus time method or two linear reservoirs in series, and the outflows from subsurface and groundwater (baseflow) storage are simulated using a single linear reservoir approach. Two channel routing methods are available: lag and route, and Muskingum-Cunge. The storage indication or Puls method is used for reservoir routing.

Input and output can be specified in either Imperial or S.I. units and the program can be run on micro- or mainframe computers. For ease of operation during multiple event runs (e.g., calibration and design flow work), the program has been set-up to read input data from two files; the first file contains event related information (e.g., rainfall data, and observed hydrographs), and the second file contains watershed characteristics (e.g., soil parameters and channel cross-sections).

4.3 MODEL DEVELOPMENT

This section summarizes the relevant aspects of the development of the GAWSER model for GRCA. Readers are encouraged to read the GAWSER Training Guide and Reference Manual (Schroeter and Associates, 2004) for additional details.

4.3.1 Climate Data

As discussed in Section 2.4, precipitation is spatially variable across the watershed and to represent this variability, the GRCA divided the watershed into "Zones of Uniform Meteorology" (ZUMs), as shown in Figure 40. Each of these zones represents a particular climate station, which is assumed to be representative of the average climate throughout each zone. Due to a limitation of available long term climate datasets, the full variability displayed in Section 2.4 is not able to be represented within the model.

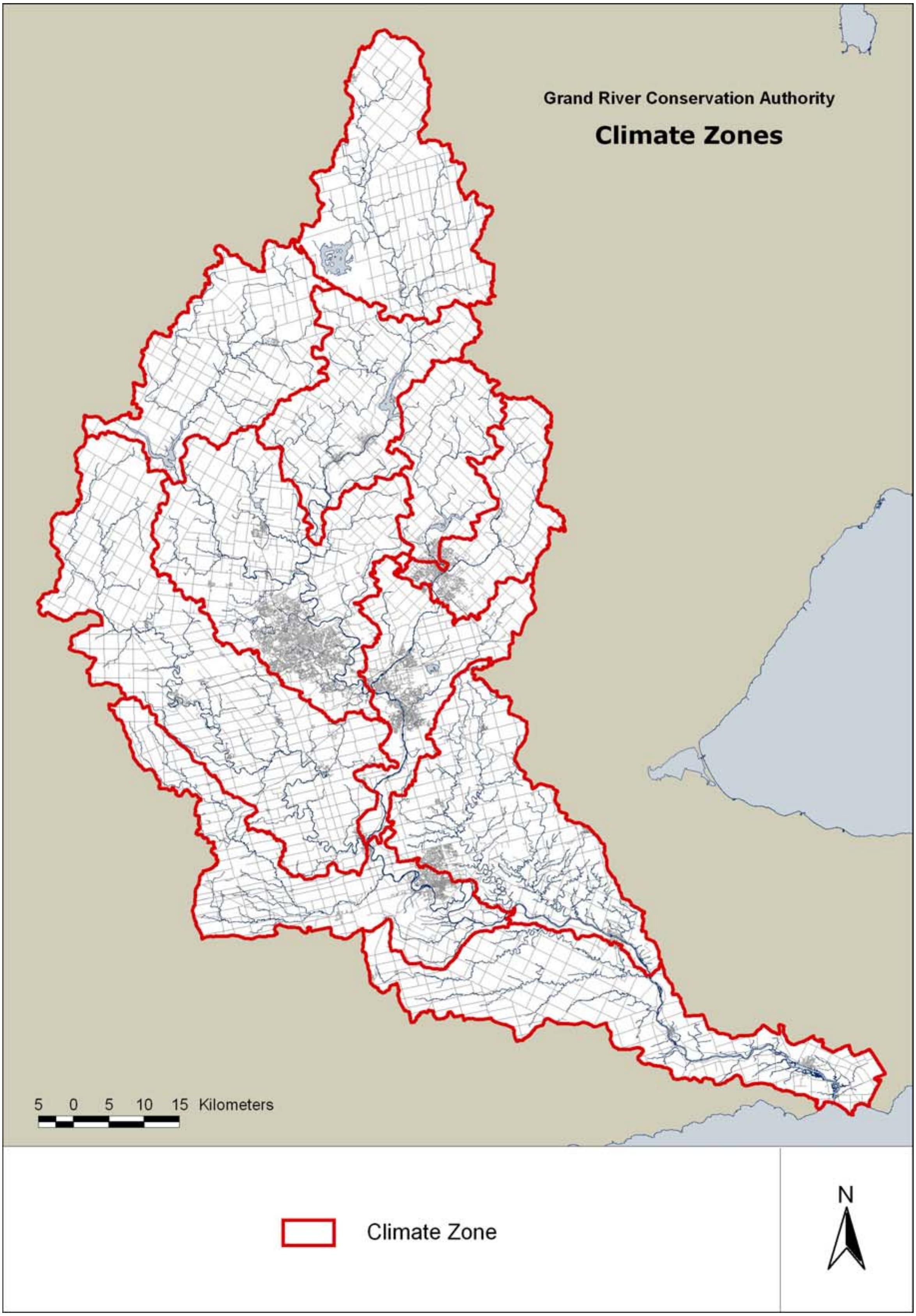

Figure 40
Zones of Uniform Meteorology

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Raw climate datasets typically include data gaps and errors due to temporarily closure of stations or equipment malfunction. The GRCA used data from adjacent stations to “fill-in” gaps using a process described in a technical paper by Schroeter et al. (2000a). For the purposes of this study, the GRCA organized, filled-in and compiled a final climate dataset from November 1960 to November 1999. This period includes two severe droughts, in the early 1960’s and in the later 1990’s.

4.3.2 Catchment Delineation

The catchments for the continuous hydrologic model match the catchments delineated per the event based flood forecast model. The Grand River watershed is divided into 136 catchments. The average size is 50 km^2, with the minimum 3 km^2 and maximum of 154 km^2. Figure 41 illustrates the spatial resolution of the catchments used. In general, the catchments were delineated to ensure that they represent small areas and streams of interest within the watershed. Over time, a number of catchments have been delineated at a very detailed level as part of subwatershed studies, and this level of detail has been included in the regional model. It is expected that this refinement will continue in the future as the GRCA studies local areas in greater detail.

4.3.3 Response Units

In order to simulate how a particular catchment would respond to a precipitation event, the physical makeup, in terms of soils, or geologic materials and land cover, of the catchment must be represented in the model. Soil permeability then determines how it will respond to a precipitation event, whether it will quickly produce large volumes of runoff (low permeability), or if there is a delayed, subdued response in stream flow (high permeability). Soil permeability varies by soil type and also by moisture content which changes throughout the simulation. Furthermore, GAWSER provides for a monthly adjustment factor for soil permeability which accounts for factors such as freezing and temporal changes in vegetation affecting evapotranspiration.

In order to promote integration between surface and groundwater models, the GRCA chose to use quaternary geology, as opposed to soil mapping, as the basis to define soil types within the model. This decision was made due to the fact that the quaternary geology is likely more representative of the factors affecting groundwater recharge. To reduce the number of quaternary geology types represented within the hydrologic model, the GRCA grouped geology types that react hydrologically similar in response to a precipitation event. This classification scheme is very broad and is done from a point of view of hydrologic modelling data. All quaternary geologic types found in the Grand River watershed were assigned to one of five groupings; Impervious; Clay Tills; Silt Tills; Sand Tills; and Sand & Gravels. The geology types that were assigned to each grouping can be found on Table 4.1. It should be noted that this grouping was done on a hydrologic basis, and may differ from the geologic definition of the materials. Past hydrologic modelling experience was also considered when determining the geologic grouping.

Table 4.1 - Quaternary Geology Grouping

Geologic Grouping	Quaternary Geology Description
Impervious[1]	Amabel Lockport Formations, Bertie Formations, Clinton & Cataract Groups, Dundee & Onondaga & Bois Blanc Formations, Guelph Deposits, Salina Formation, Open Water
Clay Tills	Canning Till, Glaciolacustrine Deep Water Deposits, Halton Tills, Man-Made Deposits, Maryhill Till, Mornington Till, Tavistock Till, Wartburg Till, Fluvial Deposits[2], Modern Fluvial Deposists[2]
Silt Tills	Port Stanley Till, Stratford Till
Sand Tills	Catfish Creek Till, Elma Till, Wentworth Till

Geologic Grouping	Quaternary Geology Description
Sand and Gravels	Eolian Deposits, Glaciofluvial ice-contact Deposits, Glaciofluvial Outwash Deposits, Glaciolacustrine Deposits Beach Bar, Glaciolacustrine Deposits Shallow Water, Modern Beach Deposits

[1] Due to the regional nature of the hydrologic model, exposed bedrock was assumed to be impervious.
[2] Pervious deposits immediately adjacent to rivers and streams were assumed to have low infiltration due to high water tables and therefore lumped with the poorly drained clays.

Similar to geology, land cover was summarized into hydrologically similar groupings. 1992 MNR land cover was used (MNR, 1995) to be consistent with the 1990-2000 calibration period. The land cover categories were as listed in Table 4.2.

Table 4.2 - Land Cover Grouping

Land Cover Grouping	MNR 1992 Land Cover Classification
Urban	Urban: Industrial/Commercial/Roads/Infrastructure, Urban: Residential
Wetland	Deep/Shallow Water Marsh, Meadow Marsh, Cattail Marsh, Hardwood Thicket Swamp, Conifer Swamp, Open Fen
Low Vegetation	Row Crops, Hay/Open Soil
Medium Vegetation	Pasture, Abandoned Fields, Savannah Prairie
High Vegetation	Dense Deciduous Forest/Shrubs, Dense Conifer, Dense Conifer: Plantations, Mixed Forest: Mainly Deciduous, Mixed Forest: Mainly Conifer, Sparse/Open Deciduous Cover

With both quaternary geology and land cover grouped into manageable categories, the datasets were overlain to create Hydrologic Response Units (HRUs). A total of 18 classifications of HRUs are needed to represent the combinations of soil type and land use covers as shown on Table 4.3. Each of these HRUs can be further classified as being hummocky or non-hummocky. This overlay creates a very detailed coverage over the Grand River watershed, and is used to define the hydrologic response of a catchment. An example of the spatial distribution of the HRU's is shown in Figure 42. Approximately 140,000 polygons make up the HRU coverage for the Grand River watershed.

GAWSER represents each type of HRU as having similar hydrologic characteristics. These characteristics include infiltration rates and groundwater recharge parameters. Each HRU is assigned to provide groundwater recharge to either a fast responding groundwater reservoir, or a slow responding groundwater reservoir. The fast responding reservoir is intended to represent shallow groundwater flow systems that respond quickly to rainfall events, typically seen in less permeable materials (interflow or tile drainage). The slow responding reservoir represents the deeper groundwater flow systems typically associated with more pervious materials. Recharge rate estimates from GAWSER include recharge to both reservoirs. Streamflow hydrographs are generated by combining the outflows from both reservoirs, as well as overland runoff.

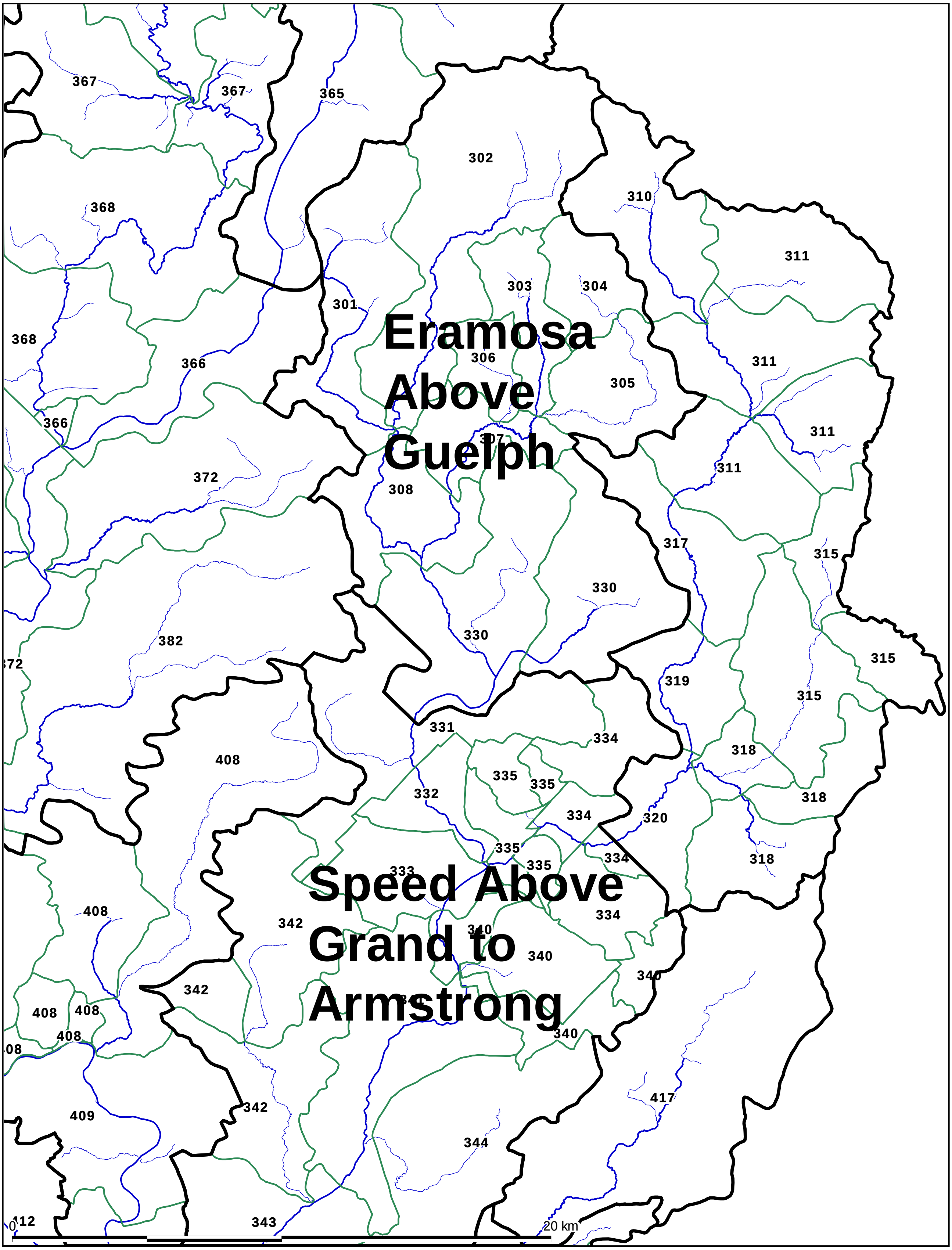

Figure 41
Catchment Delineation

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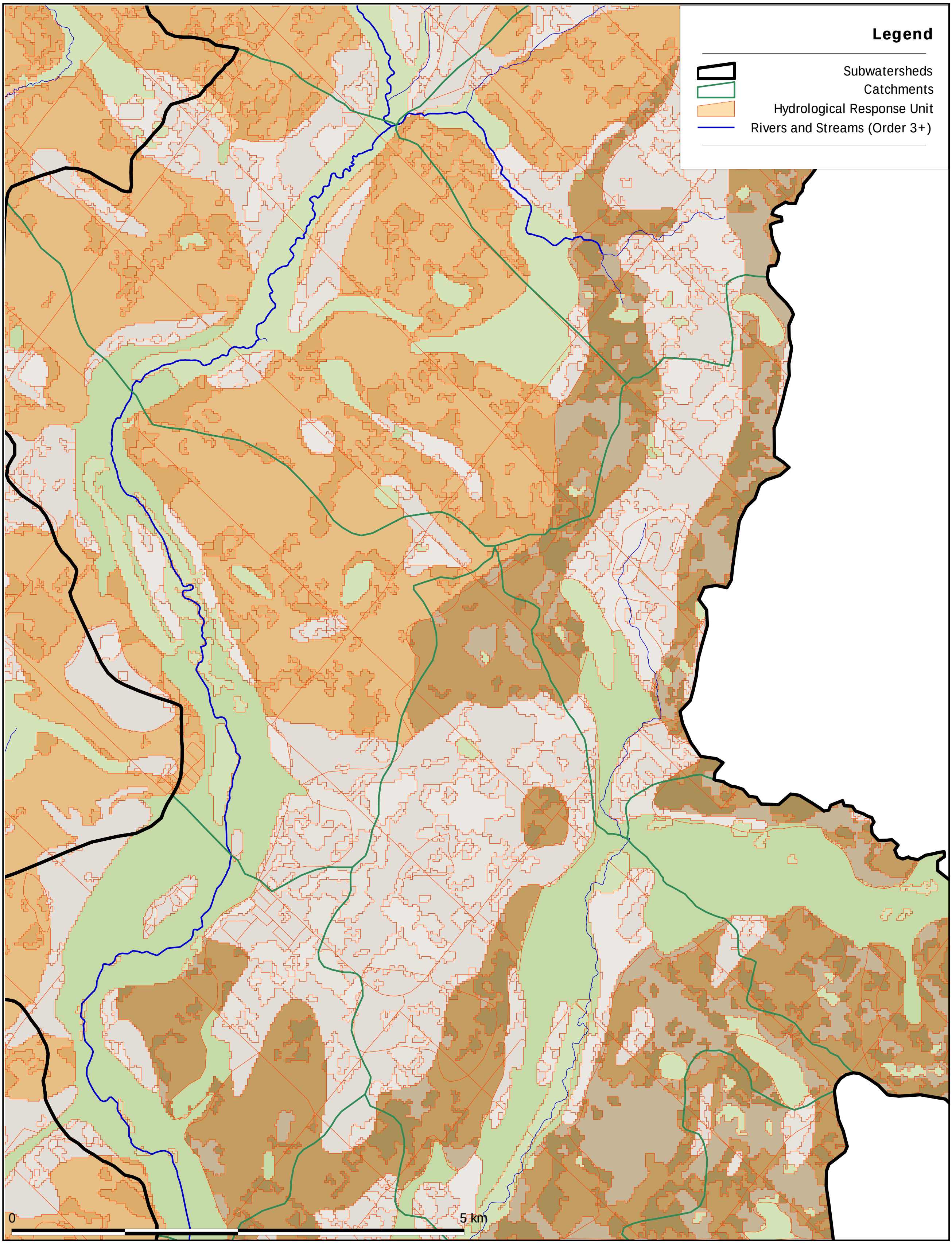

Figure 42
HRU Delineation

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Table 4.3 - Summary of HRUs

HRU	Description	Groundwater Reservoir	HRU	Description	Groundwater Reservoir
1	Impervious	NA	10	Sand Till Medium	Fast
2	Wetland	Fast	11	Sand Till High	Slow
3	Clay Till Low Vegetation	Fast	12	Sand Gravel Low	Slow
4	Clay Till Medium Vegetation	Fast	13	Sand Gravel Medium	Slow
5	Clay Till High Vegetation	Slow	14	Sand Gravel High	Slow
6	Silt Till Low Vegetation	Fast	15	Urban Clay	Fast
7	Silt Till Medium Vegetation	Fast	16	Urban Silt	Fast
8	Silt Till High Vegetation	Slow	17	Urban Sand	Slow
9	Sand Till Low Vegetation	Fast	18	Urban Sand Gravel	Slow

The top 8 pervious HRUs, by drainage area, and one impervious HRU are selected to represent the hydrologic response of a particular catchment. Typically, selecting the top 8 pervious HRUs accounted for more than 90% of a catchment's drainage area. The remaining area in HRUs was typically very small and was prorated across the top 8.

GAWSER performs water budget calculations for each type of HRU and, therefore any hydrologic component specific to a HRU can be output to file. The sum of all HRUs for a particular catchment, weighted by area, produces the outflow hydrograph for a catchment. Outflow hydrographs from other catchments are summed, and then routed to downstream locations, where calibration to observed streamflow is possible.

The breakdown of HRUs for each subwatershed is included on Table 4.4.

Table 4.4 - HRU Breakdown by Subwatershed

Subwatershed Name	Clay Till High	Clay Till Low	Clay Till Med	Sand Grvl High	Sand Grvl Low	Sand Grvl Med	Sand Till High	Sand Till Low	Sand Till Med	Silt Till High	Silt Till Low	Silt Till Med	Wet-Land	Urb Clay	Urb Sand	Urb SG	Urb Silt	IMP
GRAND ABOVE LEGATT	7.0%	25.6%	7.9%	4.7%	4.6%	1.1%	5.4%	21.6%	4.7%	0.0%	0.0%	0.0%	12.6%	0.0%	0.0%	0.0%	0.0%	4.7%
GRAND ABOVE SHAND TO LEGATT	4.5%	45.6%	7.3%	4.8%	21.5%	3.6%	0.2%	0.4%	0.1%	0.3%	0.3%	0.1%	8.6%	0.1%	0.0%	0.2%	0.0%	2.3%
GRAND ABOVE CONESTOGO TO SHAND	2.8%	39.9%	1.8%	3.3%	19.8%	0.9%	0.1%	0.4%	0.0%	1.7%	22.8%	1.1%	2.7%	0.6%	0.0%	0.2%	0.3%	1.7%
CONESTOGO ABOVE DAM	5.5%	56.1%	7.5%	2.5%	7.7%	1.1%	1.6%	14.0%	0.7%	0.0%	0.0%	0.0%	1.6%	0.0%	0.0%	0.0%	0.0%	1.6%
CONESTOGO BELOW DAM	5.1%	72.0%	0.7%	2.3%	15.3%	0.1%	0.1%	0.9%	0.0%	0.0%	1.0%	0.0%	1.0%	0.0%	0.0%	0.1%	0.0%	1.2%
GRAND ABOVE DOON TO CONESTOGO	1.6%	10.0%	0.9%	5.3%	23.1%	2.0%	0.0%	0.0%	0.0%	3.0%	27.2%	1.6%	4.7%	3.9%	0.0%	9.9%	4.6%	2.1%
ERAMOSA ABOVE GUELPH	0.8%	0.2%	0.1%	8.7%	15.5%	7.2%	7.0%	10.8%	5.6%	3.4%	18.8%	5.0%	9.6%	0.0%	0.0%	0.0%	0.0%	7.3%
SPEED ABOVE DAM	1.3%	1.4%	0.5%	10.5%	29.2%	7.7%	0.0%	0.0%	0.0%	4.6%	29.9%	5.7%	7.1%	0.0%	0.0%	0.0%	0.0%	2.1%
SPEED ABOVE GRAND TO Dam	1.3%	1.9%	0.7%	7.0%	27.9%	5.3%	1.2%	4.6%	1.9%	1.9%	23.7%	3.1%	5.1%	0.3%	0.1%	5.9%	5.2%	3.0%
MILL CREEK	0.7%	0.1%	0.4%	10.7%	18.0%	9.2%	11.4%	20.9%	12.6%	0.0%	0.0%	0.0%	14.0%	0.0%	0.0%	0.0%	0.0%	2.0%
GRAND ABOVE BRANTFORD TO DOON	1.5%	5.3%	0.7%	7.0%	27.2%	2.7%	5.1%	13.2%	2.4%	0.2%	1.8%	0.1%	3.7%	3.9%	1.8%	18.3%	1.4%	3.5%
NITH ABOVE NEW HAMBURG	5.3%	65.1%	1.7%	1.9%	9.3%	0.5%	0.2%	3.7%	0.0%	0.8%	8.0%	0.1%	2.7%	0.2%	0.0%	0.0%	0.0%	0.4%
NITH ABOVE GRAND TO NEW HAMBURG	3.0%	18.8%	0.5%	6.5%	39.6%	1.3%	0.4%	3.7%	0.1%	1.4%	19.3%	0.3%	3.4%	0.0%	0.0%	0.1%	0.0%	1.7%
WHITEMANS CREEK	3.4%	21.7%	0.4%	7.3%	34.1%	0.9%	0.1%	2.5%	0.0%	2.3%	23.0%	0.5%	3.6%	0.0%	0.0%	0.0%	0.0%	0.3%
GRAND ABOVE YORK TO BRANTFORD	6.4%	60.0%	6.0%	2.5%	16.3%	1.1%	0.2%	1.4%	0.1%	0.0%	0.0%	0.0%	0.4%	2.5%	0.0%	1.1%	0.0%	1.9%
FAIRCHILD CREEK	4.4%	34.6%	3.5%	1.9%	14.6%	1.4%	3.6%	14.7%	2.7%	0.0%	0.0%	0.0%	2.6%	0.9%	0.0%	2.1%	0.0%	13.0%
MCKENZIE CREEK	22.4%	45.3%	11.8%	2.6%	11.2%	0.5%	0.3%	2.8%	0.2%	0.0%	0.0%	0.0%	0.8%	0.0%	0.0%	0.0%	0.0%	2.1%
GRAND ABOVE DUNNVILLE TO YORK	13.5%	54.8%	10.5%	2.9%	6.0%	1.0%	0.2%	1.4%	0.2%	0.0%	0.0%	0.0%	1.4%	0.0%	0.0%	0.0%	0.0%	8.1%

4.3.4 Seasonal Variation

The large seasonal changes in temperature, that Canada is so well known for, dramatically affects several hydrologic characteristics, and must be represented for in any modelling.

Seasonal shifts are particularly noticeable in reference to infiltration parameters. The difference in infiltration rates between a frozen and a thawed soil may be very significant. Areas dominated by soils with normally high infiltration rates, may produce a large proportion of runoff when frozen.

To account for this, GAWSER has been developed with the ability to vary infiltration parameters with season. Monthly adjustment factors are used to continuously modify the base infiltration rate as the model progresses through the year. These factors have been determined through modelling experience in the Grand River watershed and by Dr. Harold Schroeter's modelling experience in other southern Ontario watersheds. Included on Table 4.5 are the monthly adjustment factors for infiltration capacity used in GAWSER. Note that these factors have been estimated based on the calibration of numerous models throughout southwestern Ontario. The factors are representative of typical average monthly conditions.

Table 4.5 - Monthly Adjustment Factors for Infiltration Capacity

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.02	0.03	0.03	0.1	0.4	0.65	0.75	0.9	0.65	0.25	0.1	0.03

4.3.5 Disconnected Drainage

Hummocky topography associated with various moraine features in the watershed results in disconnected drainage patterns. Disconnected drainage affects the hydrology by trapping runoff that would drain to the stream network in large depressions, and allowing it to infiltrate over an extended period of time. Having no local drainage, this water can only infiltrate into the ground or evaporate. Even in areas with tighter soils, clays or silts, the landscape's ability to trap and retain runoff will increase the amount of water available for infiltration.

Disconnected drainage processes were replicated in the GAWSER model by overlying the hummocky topography dataset delineated on the MNDM quaternary mapping (Figure 11) with the GAWSER subcatchments. Recharge ponds are used to represent the proportion of each catchment with hummocky topography. Over these ponds, infiltration is increased, runoff is decreased and the simulated flow regime more closely represents observed conditions.

Since the GAWSER model does not directly account for disconnected drainage within an HRU, post-processing of GAWER output is required to adjust the predicted average annual recharge and runoff rates within HRUs that are contained within the delineated hummocky topography areas. These calculations are performed by determining the total average annual recharge rates predicted by the 'recharge' ponds. and distributing this recharge amongst the HRUs situated in hummocky areas. Runoff rates for these HRUs are reduced accordingly.

4.3.6 Evapotranspiration

Evapotranspiration is one of the most dominant hydrological processes in southwestern Ontario and on average accounts for more than 50% of the annual precipitation.

Evapotranspiration is calculated within GAWSER by applying a specified Potential Evapotranspiration rate to the soil column. Water that is held within depression storage is first available for evapotranspiration. When water held in depression storage is reduced to zero, the evapotranspiration routines begin to remove soil water from the first modelled soil layer. Water is removed from the second soil layer when the first soil layer reaches half of its water holding capacity. After both soil layers reach wilting point, no additional water can be evaporated or transpired until the soil water is replenished. This approach, of removing the most readily available water first, progressing to deeper soil water, and then having evapotranspiration stop altogether when soil water reaches wilting point, most closely matches the physical process of evapotranspiration. This approach to handling evapotranspiration within a water budget is shared by other hydrologic models such as HSPF (Bicknell et al., 1997).

There are currently two methods for specifying potential evapotranspiration rates within GAWSER. Traditionally, average monthly lake evaporation rates for the general area are input into GAWSER, and are assumed to be representative of potential evapotranspiration rates. Through linear interpolation, these average monthly rates are used to generate daily estimates of potential evapotranspiration. This evapotranspiration method is used in the current GAWSER model.

GAWSER also has the capability of utilizing the Linacre evapotranspiration model, a derivative of the Penman’s equation. For a detailed explanation of the Linacre evapotranspiration model see Linacre (1977). The Linacre model uses a number of assumptions, relating maximum and minimum temperatures (widely collected values) to solar radiation and dew point temperatures (infrequently collected values). The Penman equation, which requires solar radiation and dew point temperature, is simplified and can be used with the basic climate values. This methodology of estimating potential evapotranspiration is essential when attempting to simulate the impacts of climate change, where future potential evapotranspiration may look markedly different.

4.3.7 Sewage Treatment Plant Flows

Any modeling of the watershed must take into account significant human influences. Because the Grand River and its tributaries are used as a repository for sewage treatment plant effluent, baseflow is artificially elevated. This is particularly important for the Grand through Kitchener / Waterloo, where the STP flow contribution may comprise 13% of baseflow, or up to a third in the case of the Speed River downstream of the City of Guelph.

In order to account for this the GRCA has incorporated STP discharges into the GAWSER model. STP outflow hydrographs are summed with the streamflow hydrograph at the point of discharge.

4.4 CALIBRATION

The existing continuous GAWSER model is the continuation of a long history of hydrologic modeling within the GRCA. Originally developed in the late 1980s for flood forecasting purposes, the model has seen a continual improvement over the 1990s and early portion of the 2000s. During this time, the model has shifted from being an event based model, used primarily for flood forecasting, and flood line studies, to a continuous model, which seeks to quantify all portions of the Water Balance. For this reason, there has been significant resources and effort expended in the calibration/verification of the Grand River GAWSER model.

Past calibration exercises for the continuous GAWSER model approached the calibration in a structured hierarchical approach. The model was typical calibrated to a longer temporal scale, and then sequentially moved to a shorter temporal scale. By starting to calibrate to annual volumes, moving to monthly volumes, then finally to daily flows, large problems such as climate data inputs were remedied before groundwater contributions, for example. In addition to comparing annual, monthly and daily volumes, ranked duration curves were compared for both the simulated and observed flow series, as well as ranked difference curves, which plotted the actual difference between simulated and observed flows.

Initial feedback from the groundwater model indicated that GAWSER was producing insufficient recharge and as a result both the FEFLOW model and GAWSER model were underestimating groundwater discharge. For this reason, it was decided to revisit the calibration/verification to determine if recharge rates could be increased while maintaining the model's acceptable calibration to higher runoff flows.

Although the model was simulated for the entire climate period ranging from 1960 to 1999, the results for November 1990-November 1999 were considered for calibration..

4.4.1 Parametric vs. Non-Parametric Statistics

Previous calibration exercises, as described above, focused primarily on parametric statistics (i.e. mean flow) to compare simulated and observed flow volumes. Calibrating to a mean annual or monthly flow is an important first step, as it satisfies an initial objective to ensure that the total available water budget and climate dataset is reflective of observed conditions. Due the fact that streamflow follows a lognormal statistical distribution, the mean annual or monthly flow reflects higher streamflows that are only observed over a short period of time.

By definition, median flow is a parametric statistic representing streamflow which is observed 50% of the time. In addition, the median flow is more reflective of baseflow conditions, and as a result, is a better calibration target when trying to estimate groundwater recharge. In the current study, the calibration approach focused on matching median flows to better represent monthly low flow conditions

4.4.2 Calibration Results

Plots of comparisons between observed and simulated medians were plotted for roughly 20 gauge stations in the Grand. Monthly means, and ranked duration plots were also plotted to ensure other components of the hydrograph were well simulated.

Initial comparisons of simulated and observed monthly medians did show that simulated flows were regularly lower than observed flows during low flow periods. This would indicate that the GAWSER model was in fact not producing sufficient recharge to sustain the most frequently observed streamflow during low flow periods. This confirmed the initial feedback from the groundwater model. Monthly means, or volumes, matched well, which indicated that the simulated flow regime was being affected by the climate data issue described above.

By focusing on hydrologic processes within GAWSER that affect generated recharge, simulated median monthly flows match observed median flows much more closely. The modified processes are limited to the seasonal adjustments that vary water's movement through the soil column, with month. This work is focused on the seasonal parameters for the months that act as a transition between cold and warm seasons. Particular care is taken to ensure summer median flows are being represented accurately.

Plots of mean monthly, median monthly and ranked duration comparisons for simulated and observed flows can be found in Figures 43-45 for the Nith River at Canning, the Eramosa River Above Guelph and the Conestogo River at Drayton. All these stations measure streamflow discharging from unregulated basins, and represent reliable representation of the Grand River watershed.

As described in earlier sections, the Nith River at Canning has a rather large drainage area of just over 1000 km^2. The watershed is composed of tight tills in the upper portion of the basin, changing to sandy-gravels dominating the downstream portion and heavily influenced by the Waterloo Moraine. Both monthly median and mean flows match quite well, likely due to the fact that more than one climate station is used to represent climate, therefore more accurately estimating total precipitation volume. The ranked duration curve deviates slightly in the 50-60% flow range; however, the overall fit is good.. As would be expected, the transition seasons (spring / fall), where hydrologic parameters can radically shift, shows the poorest fit between simulated and observed flows.

The Eramosa River Above Guelph is a groundwater-fed system that drains approximately 230 km^2. High amounts of hummocky topography capture surface runoff, allowing increased infiltration to occur. As with the Canning gauge, median low flows match very well. Mean simulated summer flows are on average higher than observed, which may point to an over-reliance on one climate station. Median and mean flows for the fall demonstrate a much better fit than the Canning gauge. However simulated median spring flows are significantly lower than observed, which likely points to the timing of snowmelts being an issue.

The Conestogo River at Drayton is a flashy, runoff-driven system, whose drainage area is approximately 330 km^2. Median simulated flows match observed median flows extremely well in the April-August period. Simulated and observed seem to deviate in the month of September; however, it is a relatively small difference, of less than 0.1 m^3/s. Simulated summer mean flows, however, do not match observed flows well. This is due to localized precipitation events being captured by climate stations and then being used to represent the average climate over an area. Because this gauge is more runoff driven, the effect of localized precipitation events is more pronounced. The match to the ranked duration curve is acceptable over most of the flow regime; however simulated and observed flows seem to deviate for extreme low flows (>85%). This could either point to a small regional groundwater discharge that is sustaining flow in the Upper Conestogo, or that the rating curve for the gauge station is not accurately measuring flow at the low end of the regime.

While differences between the simulated and observed flow datasets do exist, it is important to keep in mind that any model is a simplification of reality. Models are not designed to simulate every process that may affect hydrology. Differences between simulated and observed data should be expected, due to both simplified representation of reality and measurement error in observed datasets. That being said, by comparing observed and simulated flows, it can be said with some confidence that the continuous GAWSER model is reasonably predicting the hydrologic response for areas within the Grand River.

4.5 SUMMARY OF GAWSER OUTPUT

As described previously, GAWSER continuously computes the primary water budget parameters for each of the HRUs distributed across the watershed. This allows for a daily record of such hydrologic parameters as: infiltration; groundwater recharge; soil water content; direct overland runoff; evapotranspiration; and depression storage, for the period from November 1960-November 1999. An example of such output is included in Figure 46. This graph, presented with two Y-axes, illustrates the response of Sand & Gravel with High Infiltration Capacity. The right Y-axis, in reverse order, shows how soil water and infiltration varies throughout the year. When infiltration occurs following a precipitation event, the soil water correspondingly increases. Groundwater recharge and evapotranspiration are plotted with respect to the left Y axis. By comparing groundwater recharge and evapotranspiration to soil water, one see where soil water levels are high, groundwater recharge occurs. In addition to the individual water budget parameters, GAWSER can also output the simulated hydrograph for any junction point between two of the 136 catchments.

Included in Figures 47 and 48 are the annual totals of groundwater recharge and runoff on a HRU basis. As expected, recharge rates increase and runoff amounts decrease with higher permeability soils. Higher vegetation coverage has the effect of reducing runoff and increasing recharge. Runoff is minimized and recharge is increased for HRUs contained in hummocky areas. The hydrology of urban HRUs tends to be characterized by having very high runoff and low recharge rates. Wetland HRUs have a simulated average hydrologic response similar to clay tills.

Due to the climatic differences across the 13 ZUMs, the hydrologic response varies for the same HRUs located in different subwatersheds. Table 4.6 summarizes the range and average of runoff and recharge rates (mm/year) predicted for each HRU. It also summarizes these values for HRUs contained within hummocky areas.

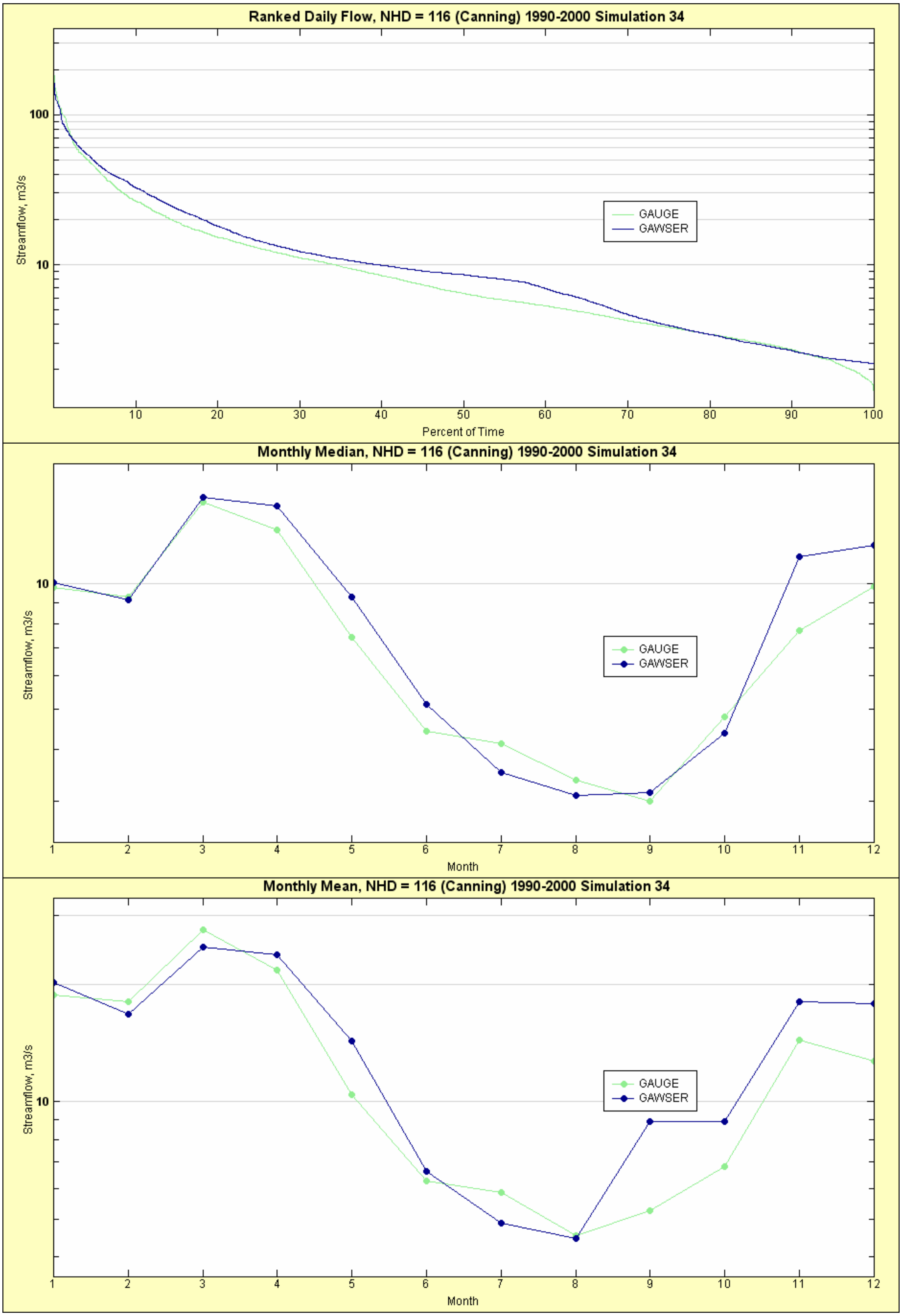

Figure 43
GAWSER Calibration (Nith at Canning)

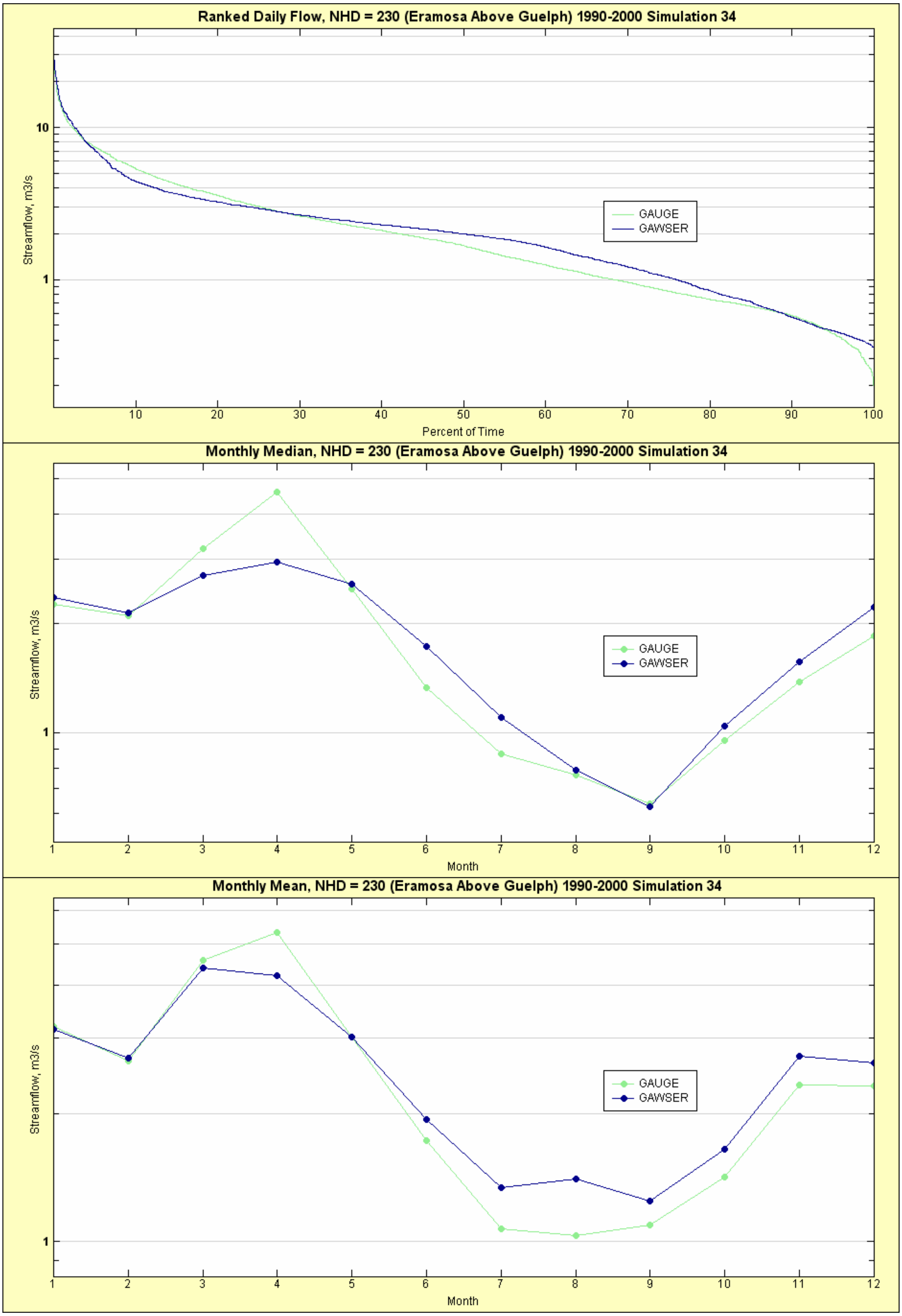

Figure 44
GAWSER Calibration (Eramosa River Above Guelph)

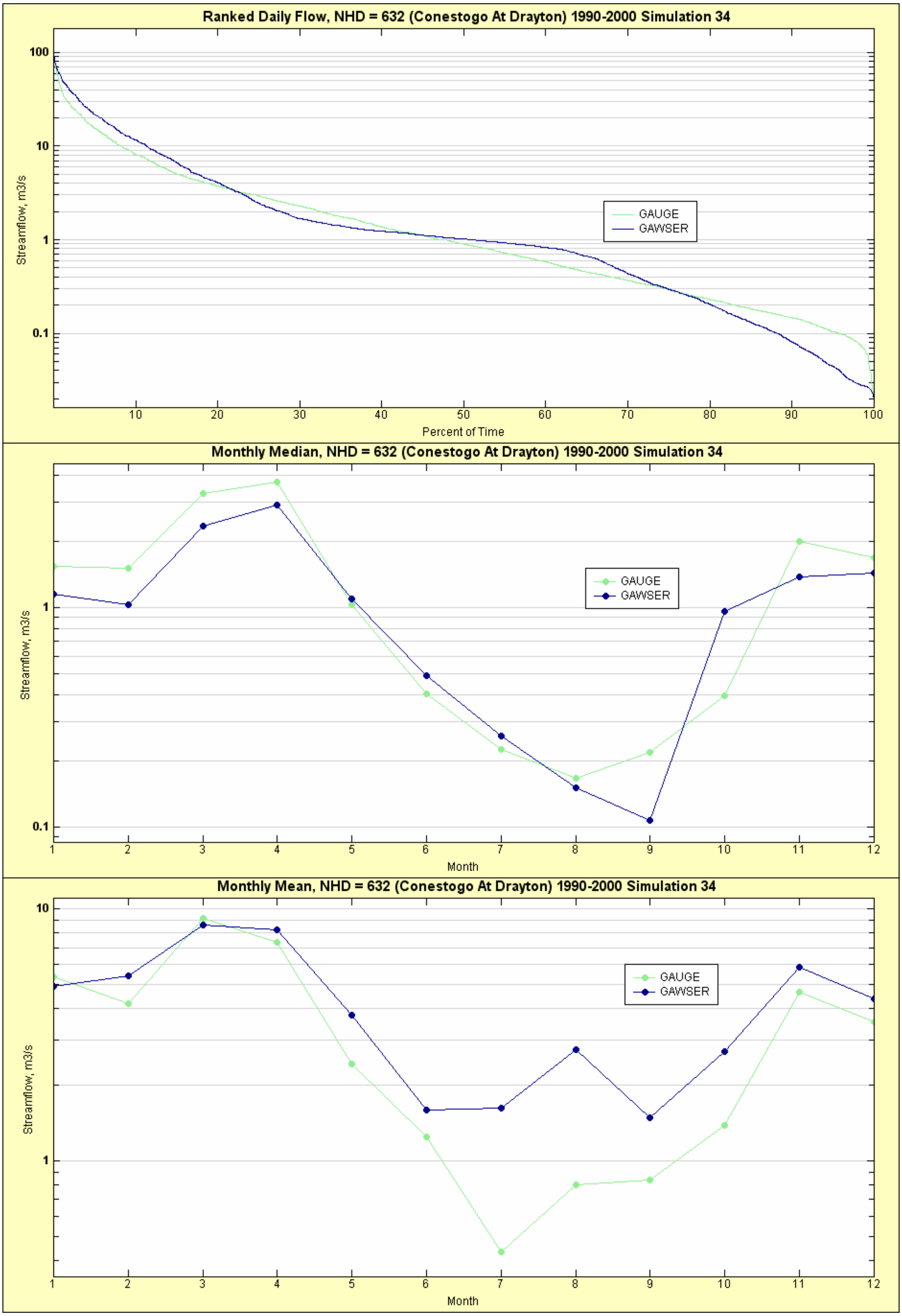

Figure 45
GAWSER Calibration (Conestogo at Drayton)

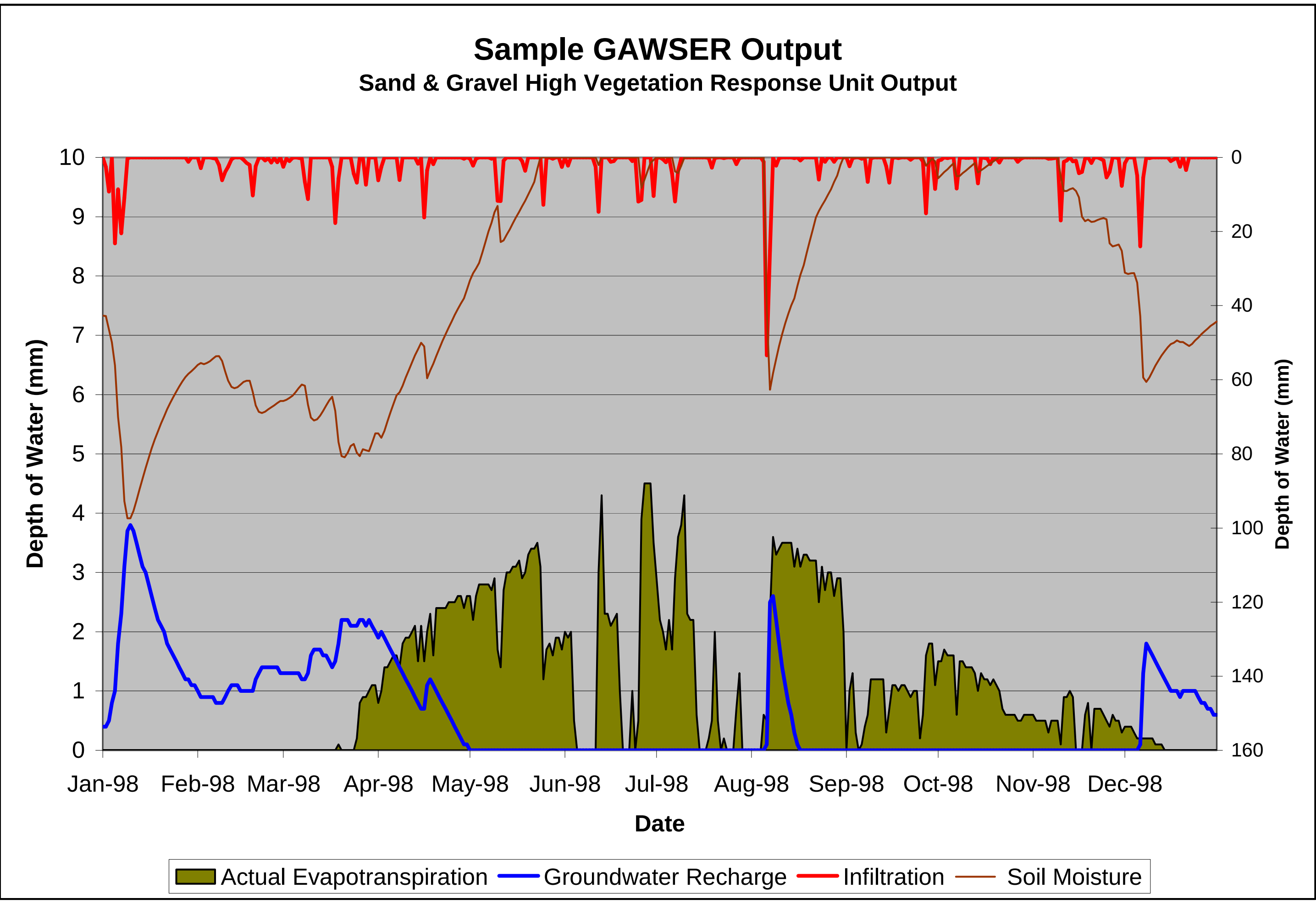

Figure 46
Sample GAWSER HRU Output

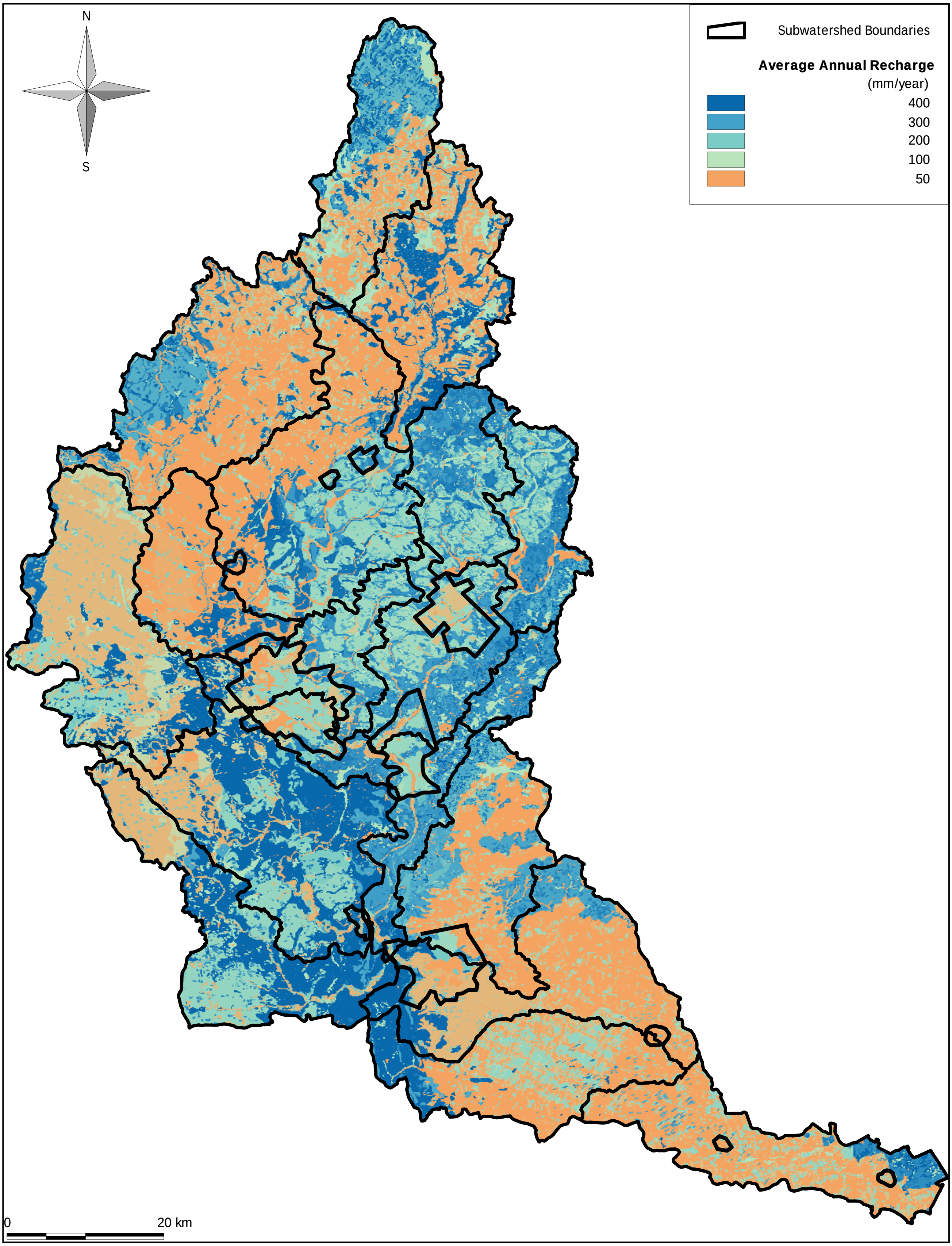

Figure 47
Recharge (HRUs)

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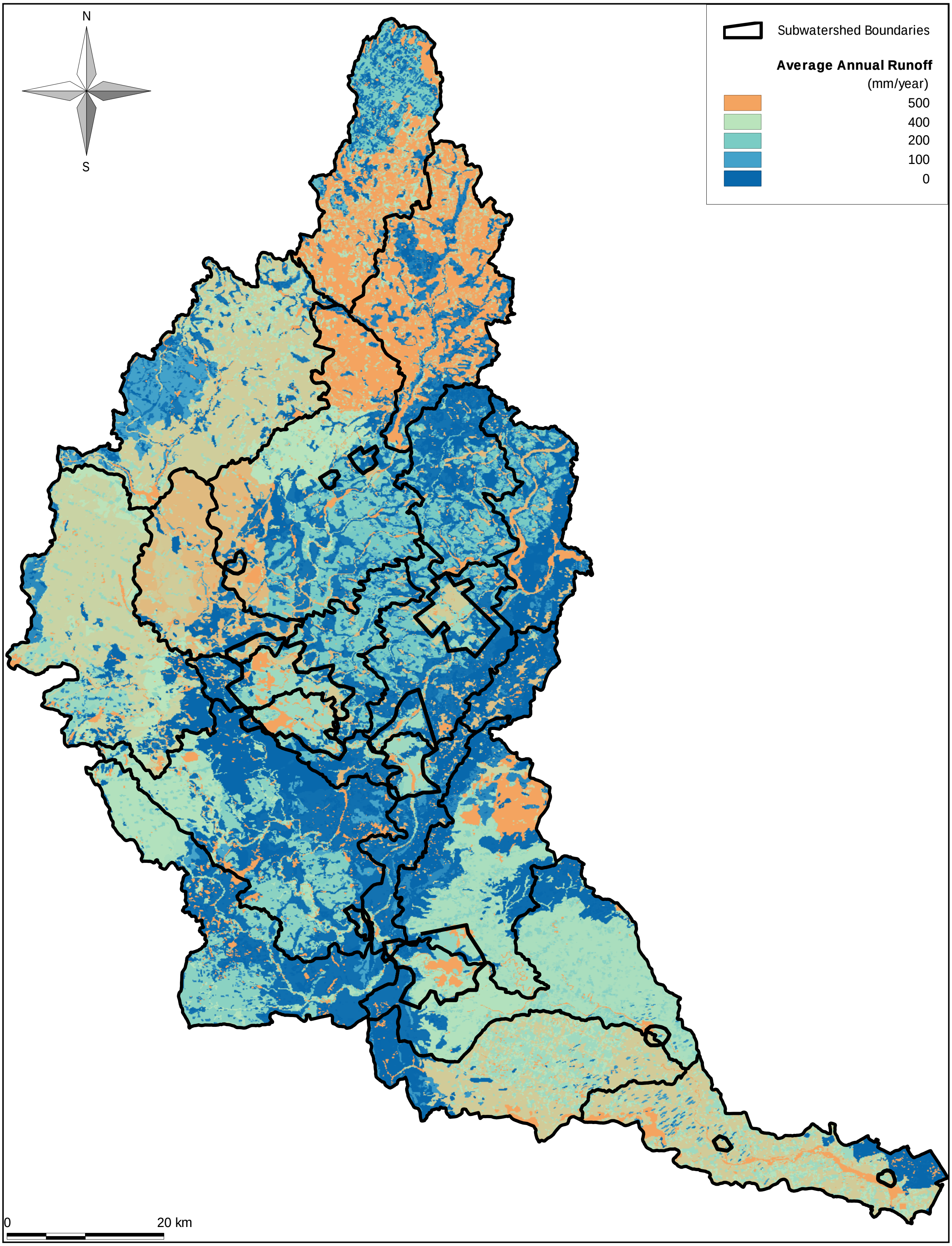

Figure 48
Runoff (HRUs)

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Table 4.6 - Simulated Runoff and Recharge Rates

Soil / Land	Vegetation	Hummocky	Runoff (mm/year)			Recharge (mm/year)		
			Min	Max	Average	Min	Max	Average
Impervious	NA	NA	727	829	767	0	0	0
Wetland	NA	NA	457	573	499	111	113	112
Clay Till	Low	No	302	503	407	32	66	45
Clay Till	Low	Yes	0	480	292	55	89	68
Clay Till	Med	No	388	456	423	75	80	79
Clay Till	Med	Yes	0	433	304	98	103	102
Clay Till	High	No	180	375	278	150	209	175
Clay Till	High	Yes	0	352	202	173	232	201
Silt Till	Low	No	193	300	206	140	164	148
Silt Till	Low	Yes	0	268	78	172	196	180
Silt Till	Med	No	99	99	99	232	232	232
Silt Till	Med	Yes	0	67	21	264	264	264
Silt Till	High	No	34	65	37	270	363	277
Silt Till	High	Yes	0	33	2	302	395	307
Sand Till	Low	No	79	201	120	237	298	271
Sand Till	Low	Yes	0	58	7	318	387	342
Sand Till	Med	No	52	54	53	325	354	337
Sand Till	Med	Yes	0	0	0	379	430	410
Sand Till	High	No	0	10	2	286	423	366
Sand Till	High	Yes	0	0	0	287	423	309
Sand Gravel	Low	No	15	45	26	307	409	354
Sand Gravel	Low	Yes	0	0	0	325	497	390
Sand Gravel	Med	No	4	8	8	351	402	355
Sand Gravel	Med	Yes	0	0	0	359	479	377
Sand Gravel	High	No	0	1	0	351	482	410
Sand Gravel	High	Yes	0	0	0	355	527	430
Clay Till	Urban	NA	515	655	566	17	30	25
Silt Till	Urban	NA	436	477	447	70	80	73
Sand Till	Urban	NA	400	400	400	147	147	147
Sand Gravel	Urban	NA	305	337	312	154	204	167

4.5.1 Temporal Variability of GAWSER Predictions

The water budget parameters reported up to this point in the document have been determined based on average results of the simulation period. Although the underlying calculations are more detailed, the results provide insight into the spatial variability of water budget parameters across the Grand River Watershed, and into the average hydrologic response associated with combinations of geology and land cover. However, hydrologic conditions exhibit a high degree of temporal variability. Hydrologic parameters including runoff and stream flow exhibit variability that can be measured on a scale of hours, while the variability of hydrogeologic parameters can be considered over a longer period.

4.5.1.1 Annual Variability - Recharge

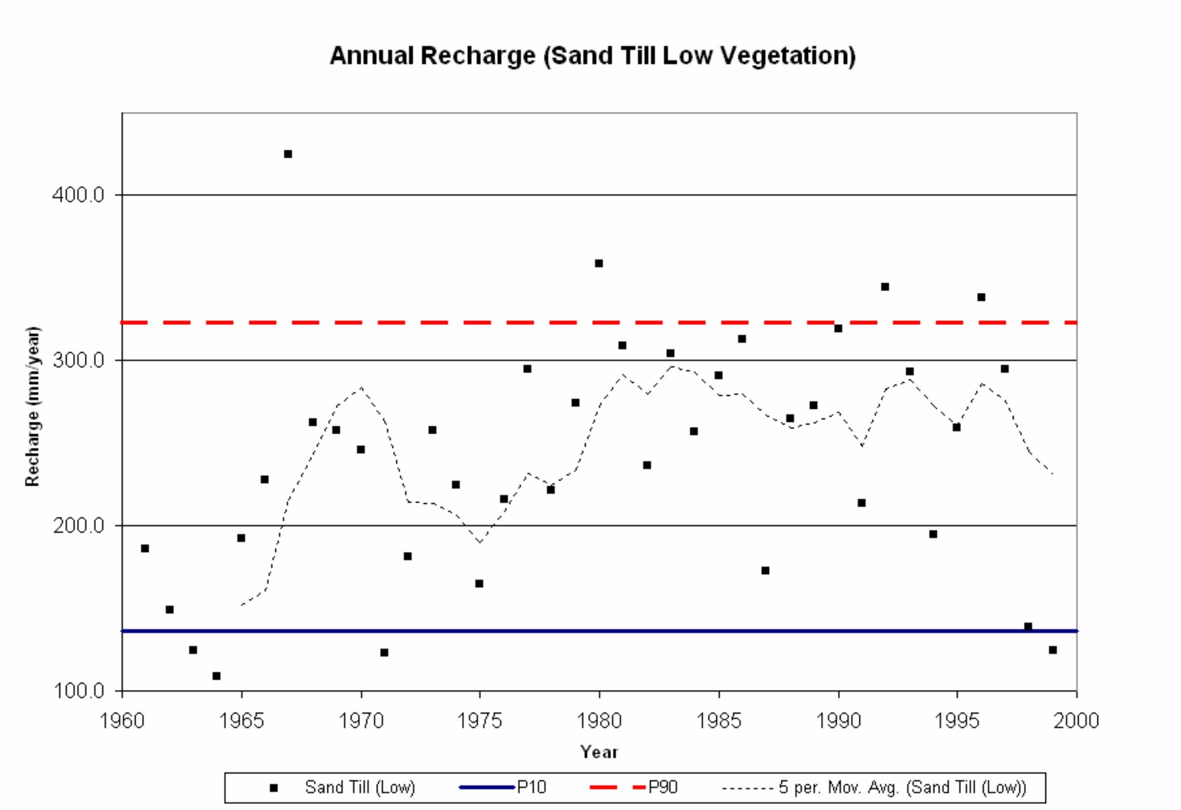
Figure 49 shows the annual recharge rates for the Sand Till (Low Vegetation) and Sand & Gravel (High Vegetation) for the Upper Grand. These HRUs were selected only to assist in visualizing the annual variability that one should expect in determining Water Budget parameters. These plots show that the annual variability of groundwater recharge rates is very significant, and that the average values considered do not fully represent the actual range that may be encountered..

In spite of its variability, groundwater flow systems move relatively slowly and on the regional scale do not respond immediately to annual fluctuations in recharge rates. The plots included in Figure 49 show the 10th and 90th percentile lines, which encompass 80% of the annual recharge estimates. In addition, a 5-year moving average of the annual recharge estimate is shown. This moving average period was arbitrarily selected to represent a time-period where groundwater systems may show significant response to a long-term change in recharge. The choice of this moving average period suggests that average groundwater recharge rates remained relatively consistent from 1980 to 1999. The five-year moving average showed a higher level of variability during the 1965-1980 time period. These charts suggest that average recharge rates calculated over a long period (i.e. 1960-1999) may not be as appropriate as those calculated over a shorter period when the moving average remains somewhat constant.

4.5.1.2 Monthly Variability - Recharge

While steady-state estimates of groundwater recharge are typically made to satisfy groundwater investigations and assessments, monthly variations of recharge are important for shallow and local groundwater systems and ecological systems.

Figure 50 presents a box and whisker diagram summarizing the variability of monthly recharge for a Sand and Gravel (High Vegetation) HRU in the Upper Grand. This HRU was selected to assist in visualizing the monthly variability that water budget parameters can experience. Similar to the case for the annual recharge variability, there is a large spread between the minimum and maximum estimates for each month. However, the differences between the 1st and 3rd quartiles are not as large, and the mean estimate demonstrates a clear seasonal groundwater recharge trend. Most of the annual recharge occurs in the March-May (Spring) period, followed by the October-December (Fall) period. Recharge rates in the summer time are typically zero when soil water is lower than field capacity. Isolated higher estimates occur during periods of extended rainfall with saturated soils well above their field capacities.



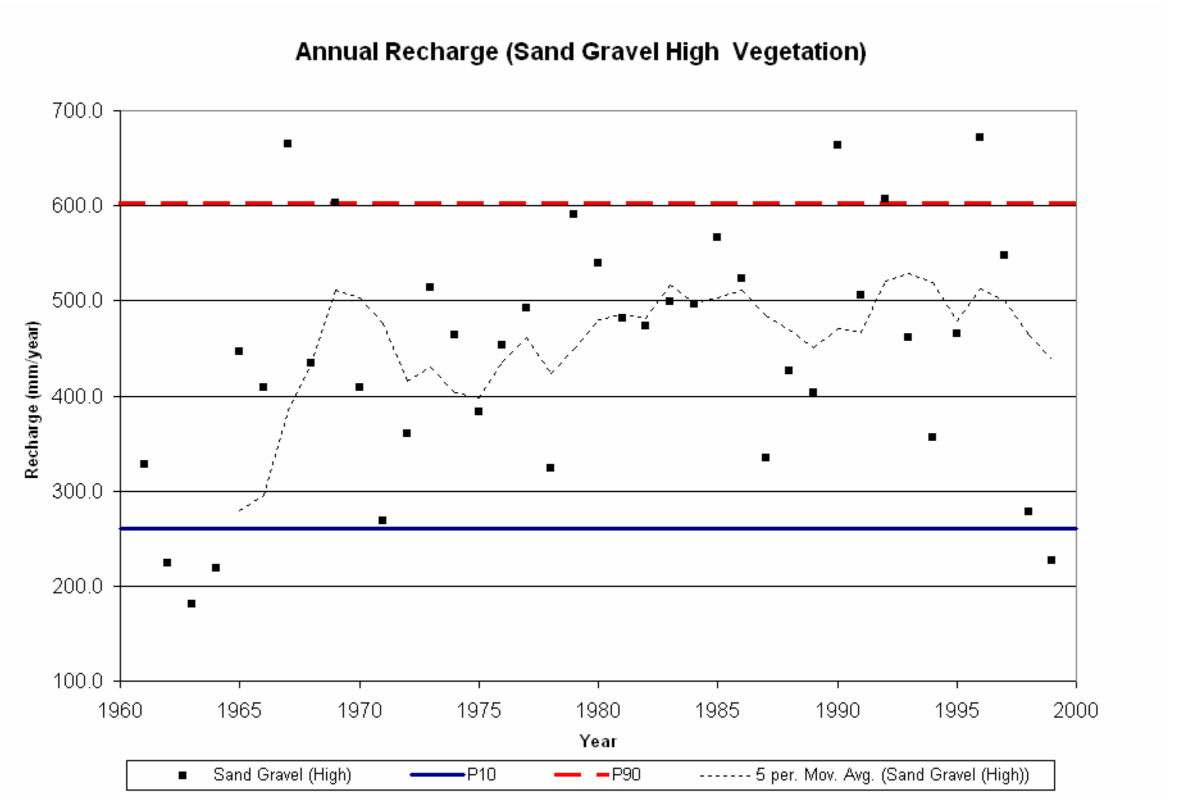


Figure 49
Annual Recharge Variability

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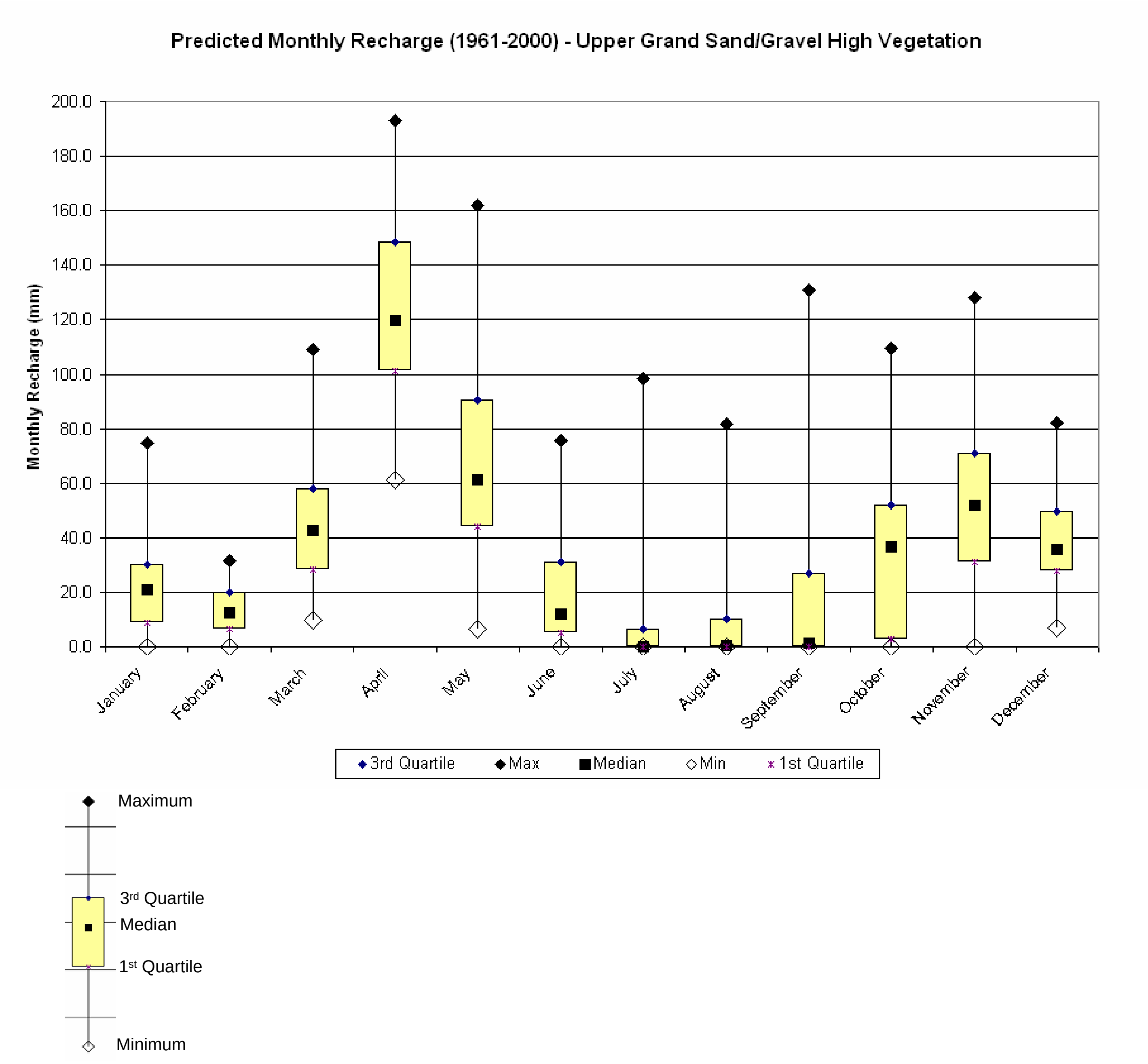

Figure 50
Monthly Recharge Box & Whisker Diagram
(Sand/Gravel with High Vegetation HRU)

4.6 UNCERTAINTY

Many elements of the water budget modelling process using GAWSER are subject to uncertainty. Although the calibration process is performed in an attempt to reduce uncertainty, the model results and water budgets reflect the uncertainty in the input parameters.

The following sections summarize some of the uncertainties associated with the GAWSER modelling process and discuss some of the potential impacts of this uncertainty.

4.6.1 Watershed Characterization

The GAWSER model is designed to reflect general characteristics of each catchment relating to land cover, soils and vegetation, and stream and river hydraulics. All model parameters are generally assigned and calibrated to represent streamflow across the watershed; however, in many areas of the watershed the level of characterization has not been refined in support of local-scale calibration and as a result, local streamflow estimates may be subject to higher levels of uncertainty.

Important watershed characterization elements subject to uncertainty are listed below:

- Hydrologic Response Units. GRCA has delineated the watershed into 18 different types of HRUs based on landuse, vegetation, and surficial geology to account for the variability in regional conditions across the watershed. This simplification accounts for larger-scale differences in landcover, but may not exactly reflect local conditions. The effects of slope on hydrologic response were not considered within HRU type and this may also impact local areas.

- Hummocky Topography Representation

  Hummocky topography mapping was used to delineate areas of the watershed that do not have outlets directly connecting to the surface water drainage system. Runoff from such areas, is directed to recharge ponds, which represent the large scale depressions, or potholes, that are commonly found in areas with hummocky topography There is uncertainty regarding the exact area of hummocky topography. Inconsistent approaches to delineate hummocky areas also introduce uncertainty into how these areas are represented in the model. Local hydrologic conditions within hummocky areas, such as varying evapotranspiration rates, have also not be accounted for.

- Snow Processes

  Snow accumulation, ablation, redistribution and melt are extremely significant hydrologic processes in Canadian watersheds. The rates of these processes are determined by the inter-relation of many factors, including; land cover, albedo, solar radiation, wind speed/direction, cloud cover, temperature fluctuations, rainfall amount/temperature and new snow density. The state of science with respect to the impact of these factors, and their effect on snow processes introduces a level of uncertainty into hydrologic modelling.

- Small Reservoirs / Online Ponds

  There are small reservoirs/online ponds within the Grand River watershed, that are not included within the GAWSER model. The ponds typically have no active reservoir operations, and are run-of river structures. While these structures do not alter infiltration processes responsible for precipitation partitioning, they may have an impact on in-channel routing. This may introduce a small level of uncertainty into the simulated hydrographs that are used for event-based calibration purposes. However, these effects are considered small when averaging over the longer term.

- Wetlands

  The GAWSER model assigns a single hydrologic response to all wetlands, regardless of the specific hydrologic function of each wetland. Wetlands found within a groundwater discharge area, may have an unlimited supply of water to sustain vegetation growth and high evapotranspiration rates. These types of wetlands would likely have an outlet to allow surface runoff/groundwater discharge to reach watercourses. Wetlands may also serve as groundwater recharge areas, may also have high evapotranspiration rates, but may not have an outlet to the surface water system. At the regional scale, the model's representation of wetlands is not significant in terms of water budget results; however, these effects may be more significant when evaluating local scale hydrologic conditions.

- Urban systems

  Urban systems, and their associated storm water management infrastructure (storm water ponds, infiltration galleries, etc...), are not explicitly modelled within the regional GAWSER model. Urban areas are represented within the model as having high imperviousness, and the assumption of not including stormwater drainage would have an impact on the model's dynamic response to precipitation events. This assumption is not very significant at the watershed scale, but will be more important at the subwatershed scale in urban areas.

4.6.2 Climate Data

The GAWSER model relies on climate data collected at discrete locations (climate station) to be representative of conditions over a specified geographic area. The current density of climate stations with long term datasets is not sufficient to fully reflect all spatial climate variability, particularly during the summer months, where extremely localized precipitation events are common (thunderstorms).

Further uncertainty is introduced into the process by the measurement error in climate observations themselves. Uncertainty with the precipitation measurement has been estimated by CCL (2000) to be approximately ±10%, with uncertainty during winter months reaching ±20%. Precipitation measurement in winter months has a higher uncertainty due to the difficulty of measuring snowfall, which can be highly impacted by wind. These levels of uncertainty must be considered, particularly when calibrating the model to short term rainfall events.

4.6.3 Streamflow Data

Streamflow measurements have varying degrees of uncertainty which must be considered when calibrating a model. Manual flow measurements, which are used to generate rating curves (allowing the translation of river stage to river flow), may contain error of approximately ±10% to 15% (rule of thumb) Measurement error for extreme events (very low or very high flow) may be significantly higher.

In addition to uncertainty in measurements used to generate a rating curve, changes in river channel geometry may alter the accuracy of the rating curve with time. Changes in river channel geometry may be over the long term (riverbed erosion), or the short term (aquatic plant growth or river ice conditions causing backwater). Malfunctions in gauge station equipment may also lead to loss of, or distortion of, streamflow calculations.

Frequent inspections of gauge stations, manual measurements to verify rating curves, and extensive quality assurance/control carried out by both Water Survey of Canada and the GRCA attempts to limit error in streamflow estimates.

4.6.4 Limitations of the GAWSER Model

Although GAWSER is a comprehensive hydrologic model, its development is subject to a number of assumptions and simplifications which will affect the certainty of the results. Some of these limitations are summarized below:

- Scale

  Scale is a critical limitation of any regional model, and is a key limitation of the Grand River GAWSER model. With an inability to represent every hydrologic process, the model is focussed on key processes that are significant at the subwatershed scale. At the local scale however, some insignificant processes may become dominant (e.g. urban systems). When analyzing model output, it should be recognized that while results are likely representative of the subwatershed average, there may exist significant variability within that subwatershed, which may not be explicitly accounted for within the model. Caution should be taken when temporally or spatially downscaling results from any watershed hydrologic model.

- Seasonal adjustment factors

  The monthly adjustment factors that GAWSER applies to infiltration parameters representing the freezing and thawing of soils are based on the calibration of numerous models over a long period of time. While these adjustments would be representative of hydrologic conditions over the long term, they may not accurately replicate changing soil conditions seen under extremes, such as a late winter, or an early spring. This limitation is critical to when analyzing extreme events; particularly those events that may be occurring when winter, early spring, or late fall months deviate from normal. As an example, significant amounts of recharge may occur during years having warm late falls when rainfall may translate into recharge in December. The model may underestimate recharge in this case.

  It is noted that other comparable hydrologic models (i.e. HSPF) also represent monthly changes in hydrologic parameters using similar adjustment factors, and the current state of hydrologic modelling knowledge must be enhanced before these models are able to reflect actual conditions.

- Handling of interflow / groundwater discharge

  Precipitation that infiltrates into the soil column, and percolates through both evaporative soil layers, is defined as groundwater recharge. Groundwater recharge enters one of two linear reservoirs before release to the surface water system. The linear reservoirs have different time coefficients, and are used to represent a slow groundwater response (well buffered groundwater discharges), and a quick groundwater response (transient groundwater discharge, or interflow). A single HRU can direct water to either of the reservoirs, but not both. By not allowing a proportion of recharge from a specific HRU to be sent to both linear reservoirs, a geologic/land cover combination that provides recharge to both, a slow responding groundwater system, as well as interflow, cannot be represented.

- Deep Groundwater Storage

  GAWSER has the ability to redirect a specified fraction of groundwater recharge from a particular catchment to a regional groundwater storage element. Water from this regional storage element can then be returned back into the surface water system at a downstream catchment, as a crude representation of a regional groundwater flow system. However, a critical limitation of this process is the fact this storage element is not mass conservative within GAWSER. If the water contained within the storage element is not withdrawn within a set time interval (24 days), the water is lost from the model. This severely limits the ability of GAWSER to truly replicate a regional flow system, where deep groundwater recharge may remain in the system for months, to years, before discharging. This limitation is particularly noticeable during extreme low flow periods, where the surface water flow system may rely on a well buffered groundwater discharge for sustained flow.

- Evapotranspiration

  Similar to the seasonal adjustment factors, GAWSER relies on potential evapotranspiration rates, which are representative of average conditions, to determine the amount of available soilwater that can be removed. This representation of potential evapotranspiration may not fully represent the annual variability of actual evapotranspiration. However, due to the reliance of evapotranspiration on the availability of soilwater (which is considered), and solar radiation (which is fairly constant), the consequence of using average evapotranspiration rates is less than using average seasonal infiltration adjustment factors, whose variations are caused by temperature alone.

4.7 SUMMARY OF GAWSER MODEL

The current GAWSER model used to simulate the hydrology of the Grand River watershed reflects approximately 15 years of continuous improvement and advancement. Originally created for flood flow estimation, the investment in the model has been leveraged to provide flood forecasting capability as well as continuous modelling for water budget purposes. The model has been successfully tested / verified in hundreds of real time flood events by GRCA flood control staff.

In spite of uncertainties in the representation of certain hydrologic process, the GRCA GAWSER model remains one of the most advanced hydrologic simulation models in Ontario, and provides realistic water budget estimates calibrated with and verified to represent observed conditions. The seasonal evaluation of model calibration completed in this project shows that the model is simulating seasonal conditions in varying types of hydrologic environments quite well. Gross watershed estimates of evapotranspiration match independent estimates of evapotranspiration reasonably well, and the groundwater modelling carried out as part of this study has verified the predicted groundwater recharge rates. Furthermore, as would be expected, given the models original purpose, high flow estimates, and in-channel routing, are very good.

The 15 years of advancement seen with the GRCA GAWSER model represents a continuous improvement process that should be the normal evolution of any regional surface water or groundwater model. Advancements in understanding of key hydrologic processes or refined watershed characterization made within local scale modelling exercises can be absorbed into the regional model, allowing a more accurate representation of the watershed hydrology. Regional models should not be considered to be static tools, but rather tools that are continuosly built upon, and improved.