Development of a Landcover Modification Scheme for Climate Change Scenarios in WATFLOOD

by

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Abstract

The global effects of climate change are unclear, with much speculation on how these effects will manifest themselves over the next century and how society as a whole should respond to this crisis. Hydroelectric power utilities such as Manitoba Hydro are particularly concerned with the climatic effects on streamflow in river basins as these effects have direct impacts on power generation. Of particular importance is the Winnipeg River Basin (WRB) as it provides a significant source of streamflow for power generation in the Canadian province of Manitoba. The WATFLOOD hydrological model is used by Manitoba Hydro to model climate change scenarios in the WRB; however no consideration is given in the model for the climatic effects on landcover. Landcover properties, specifically the growth rates are affected by changes in temperature and precipitation – and have great potential to be heavily affected by climate change. However no hydrological models take into account the effects of climate change scenarios on landcover. This study is the first step in integrating such changes into the WATFLOOD model. The changes in temperature and precipitation from climate change scenarios alter the amount of growth in different landcover types by changing the interception capacity. This results in either more water being stored as plant interception or less depending on whether the growth is predicted to increase or decrease respectively. Upon analysis of the interception evaporation and streamflow the model was determined to be performing as expected and is a critical first step in taking landcover change into account with climate change scenarios. Future research to improve the model would be including a randomized component and a methodology to account for the shifting of dominant land class boundaries in response to changing ideal climatic growing conditions.

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1 Introduction

The effects of climate change for Canada and the world has been of serious concern to people today. Of particular concern to the province of Manitoba, Canada is the climatic effects on streamflow in river basins as hydro electricity is the dominant form of power generation in the province. To quantify these effects Manitoba Hydro, Manitoba's power utility, has initiated the first steps in testing the effects of climate change on streamflow and power generation. To achieve this goal Manitoba Hydro invested in the physically based hydrological model WATFLOOD and has provided research initiatives for the University of Manitoba Civil Engineering department to participate in this development. WATFLOOD has been coupled for use with climate change scenarios (Slota, 2009), and what is now needed is for the model to take into account the climatic effects on landcover. This is important as vegetation activity is changing with climate change (Zhang *et al.*, 2006) and in order to attain improved predictions of the resultant changes in streamflow and ultimately changes in power generation hydrological models must take changing landcover into account.

1.1 Project Motivation and Scope

In 2008 Manitoba Hydro contracted Dr. Kouwen, creator of WATFLOOD, to assist in calibrating the model for use in the Winnipeg River Basin (WRB). The extents and some details of this basin are portrayed on Figure 1.

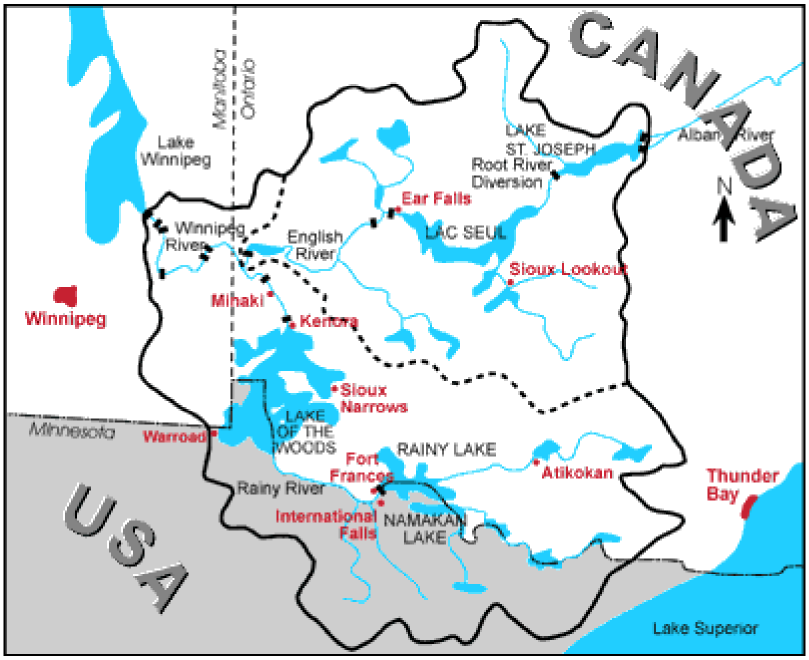

Figure 1 - Extents and Details of the Winnipeg River Basin

This basin is of particular interest to Manitoba Hydro in that it not only provides hydroelectric power to a number of small generating stations within the basin, but it is a significant source of flow to generating stations along the Nelson River downstream – which contribute most of the power generation for the province.

Current climate change simulations in WATFLOOD alter the temperature and precipitation forced into the model in accordance to predictions from Global Climate Models (GCMs) using the Delta Method (Slota, 2009). However the landcover of the watershed is assumed constant through the simulations. In fact no hydrological models exist that alter the landcover with climate change scenarios. Since the runoff generated from rainfall events is heavily dependent on the landcover type present (i.e. all things considered equal grassland would logically produce more runoff than forest land classes) this has become a serious issue to address in hydrological modelling.

1.2 Objectives of Research

The objective of this study is to enable WATFLOOD to implement the climatic effects on landcover growth over time using the climate change predictions of GCMs. This is to recognize the fact that the changes in landcover as a result of climate change may have a significant impact on future climate change simulations in WATFLOOD and decisions made by Manitoba Hydro in response to these predictions. The focus of this study will be on the changing growth of plants with climate change scenarios, while providing a foundation for future development of changing landcover in WATFLOOD.

1.3 Climate Change

1.3.1 Climate Change and WATFLOOD

WATFLOOD is a climate change enabled hydrological model that uses the Delta Method (Slota, 2009). This method changes precipitation and temperature that is forced into the model in accordance to predictions by GCMs. Different climate change scenarios can be used to create these delta values, ultimately producing output from WATFLOOD that would reflect the given scenario and time period simulated. These time periods are the 2020s, 2050s, and 2080s to represent short, medium, and long term effects of climate change respectively. The A2, A1b, and B1 scenarios are used for the simulations in this study and correspond to pessimistic, medium, and optimistic levels of greenhouse gas (GHG) emissions respectively. However in the creation of these scenarios the output of GHG emissions into the atmosphere is determined more by the results of the particular "storylines" for each scenario. These storylines offer varying accounts of population growth, advancement to renewable resources, and the level of globalization etc; and predict the changes in precipitation and temperature depending on the storyline in question (IPCC, 2000).

1.3.2 Climate and Changing Landcover

The effects of climate change are many, significantly for water resources is the resultant changes in landcover over time. Their have been many studies in regards to this phenomenon, with some of the causes stemming from increased carbon dioxide concentrations and ambient temperature. For instance the growth of *Pinus radiata* (Monterey Pine) was found to increase by 15-20% over time as a result of doubling the carbon dioxide concentrations in the air (Kirschbaum, 1999). However these were with ideal growing conditions; any deviation from the ideal in terms of temperature, precipitation, and nutrient availability would deter this growth increase (Kirschbaum, 1999).

There are many factors that determine this growth change with changing climatic conditions. Growth rates of plants are related to temperature, however the degree of which it affects the growth is also proportional to the particular species' metabolic rate and efficiency (Criddle *et al.*, 1997). Modelling these changes then presents itself to be a difficult task as each landcover type contains many different species of plants, and with the lack of metabolic measurements in the field approximations must be made.

As well as growth rates being affected by climate change there are also shifting of dominant land classes in different regions. With different temperature and precipitation conditions this may naturally result in different types of plants that have "optimal" growing conditions in that area. Through the process of natural selection this can cause new dominant landcovers in many areas. An example of this is the coniferous and deciduous forest boundary in the province of Ontario, Canada. A warmer climate favors the growth of deciduous over coniferous forest, and this boundary is found to be moving slowly northward as a result (Goldblum & Rigg, 2005).

Quilbe suggests that climate change can induce changes in above ground biomass, canopy height, and normal occurrences of wildfires (Quilbe *et al.*, 2008). In his study using climate change scenarios he modelled the Chaudiere River Basin in Quebec, Canada using pre-agriculture landcover and with present day landcover. Strong correlations were found in this study between discharge at the outlet and the dominant landcover type present in the model (Quilbe *et al.*, 2008).

Including the effects of climate change on landcover properties in hydrological models has never been done before, despite these changes having significant effects on runoff. This study is the first step in integrating landcover changes into a hydrological model.

1.4 The WATFLOOD Model

WATFLOOD is a physically based hydrological model developed by Dr. N. Kouwen of the University of Waterloo. Used not only for long term flow simulations and flood forecasting WATFLOOD is also used for climate change impact studies and determining the changes in streamflow with climate change scenarios and ultimately power generation. With a modular framework this model is ideally suited for continuous development (Kouwen, 2008).

1.4.1 Hydrological Modelling

This model uses grouped response units (GRUs) for calculating runoff in a watershed. The watershed to be simulated is divided into grids and further divided into elements of similar landcover. For example a watershed may be divided into 1000 grids, with each grid having certain percentages of dominant land classes. The hydrological response is determined for each land class, then is aggregated and routed to the outlet of the grid and ultimately to the outlet of the watershed. These concepts of GRUs are represented on Figure 2. The A, B, and C in the figure correspond to different classes of dominant landcover in a particular grid in the watershed; these proportions are determined by areal photographs.

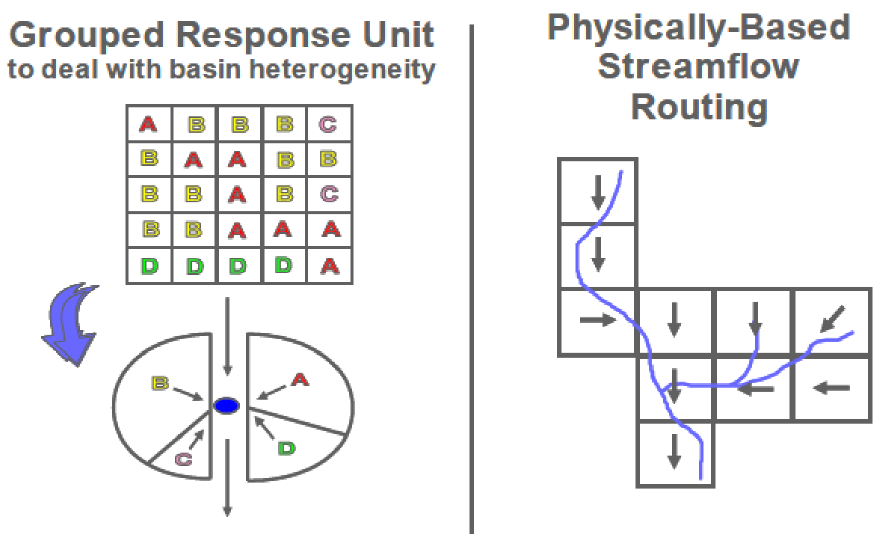

Figure 2 - GRUs in WATFLOOD (Kouwen, 2008)

With the GRU framework WATFLOOD is ideally suited for changing the properties of landcover classes real-time during simulations. Since the hydrological response calculated for each land class is aggregated, it is possible to change the properties of each land class (i.e. growth) throughout the simulation. More detailed information on the workings of WATFLOOD and the GRU framework are available in (Kouwen, 2008) and (Stadnyk-Falcone, 2008).

The hydrological processes that are modelled by WATFLOOD are included on Figure 3.

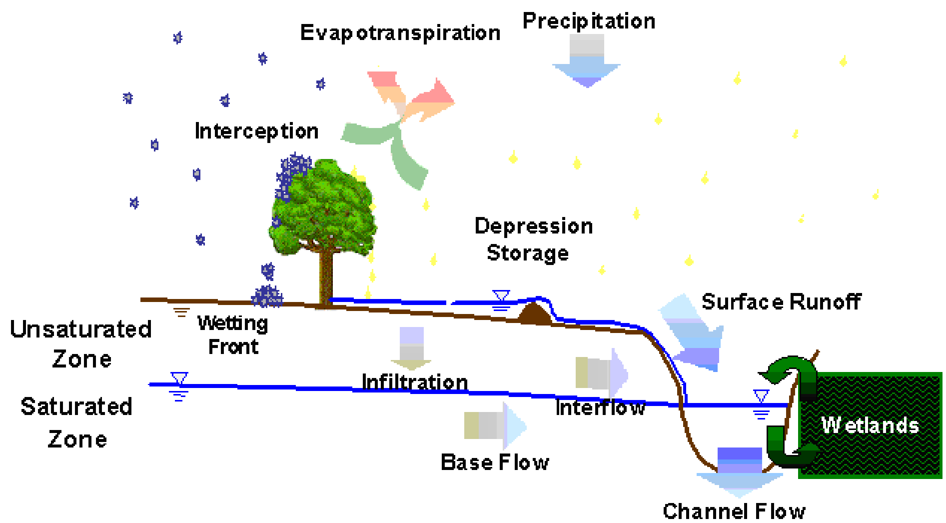

Figure 3 - Hydrological Processes in WATFLOOD (Stadnyk-Falcone, 2008)

The focus of this study however is on the interception storage. The interception storage is the amount of precipitation held within the land class during storm events and is dependent on the properties of the land class itself. In this case forest-type land classes would have a greater interception storage capacity than grassland-type land classes. It is with this mechanism that growth can be modelled in WATFLOOD. Increases in growth can be represented by an increase in interception capacity due to an increased leaf area, concentrations of leaves, and canopy height in that there would be more precipitation intercepted with this increased growth. Predictions of growth can then be made under different conditions and implemented into the model for use with climate change scenarios.

2 Project Methodology

To complete this study and its objectives listed in Section 1.2 the following steps were undertaken:

- Model development for changing landcover with climate change scenarios
- Coding the landcover modification scheme into WATFLOOD
- Performing climate change simulations in WATFLOOD with and without the landcover modification scheme in the Winnipeg River Basin

2.1 Landcover Modification Scheme Development

As indicated in Section 1.4.1 the focus of this study was to create a subroutine that alters interception capacities of land cover classes with time in response to climate change scenarios. The two parameters that are altered by climate change scenarios in the model are gridded temperature and precipitation (Slota, 2009). Therefore relationships were created between them and the interception capacity to reflect the changes in growth with climate change.

Simple linear relationships however are not possible with this approach; as there is no direct relationship between temperature, precipitation and growth. An example of such a relationship with temperature is shown on Figure 4. Changes in temperature are plotted against changes in the predicted interception capacity with linear regression unsuitable. Since there is no direct relationship there must be many other factors that influence growth in addition to changing temperatures. Too many for WATFLOOD to model not only for lack of available data (i.e.

metabolic rates mentioned in Section 1.3.2) but also for computational efficiency on simulating mesoscale watersheds.

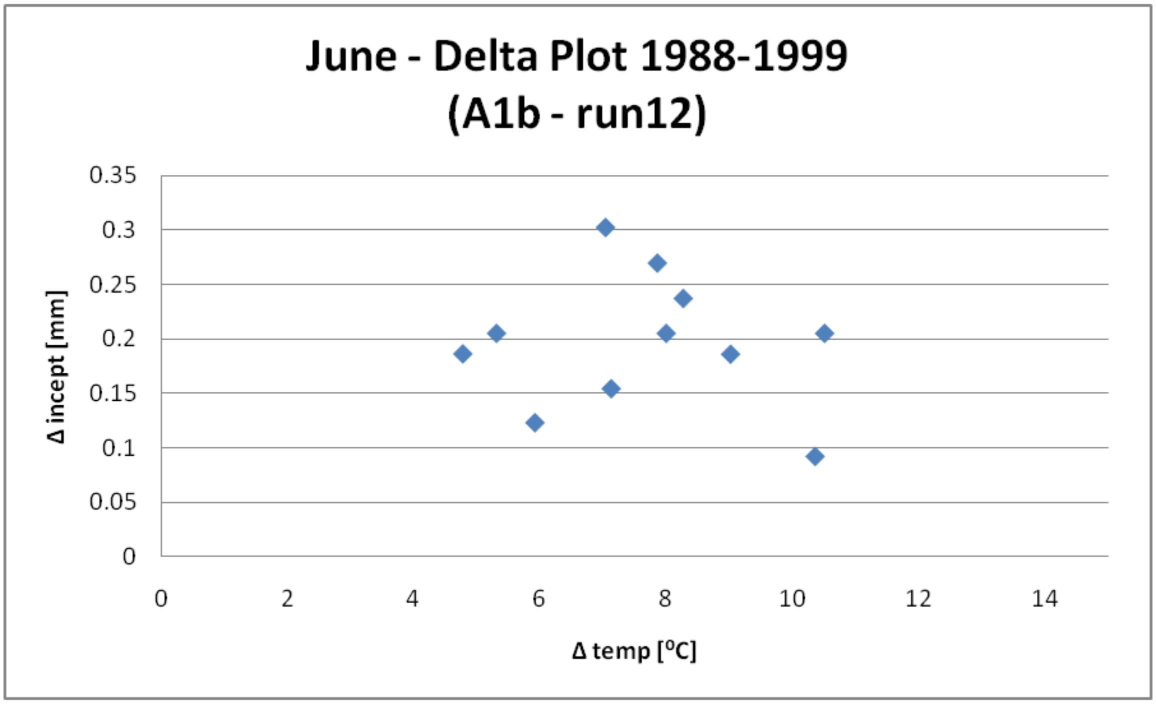

Figure 4 - Delta Plot: Relationships between Changes in Temperature and Interception Capacity

To account for this a number of cases were set up in order to capture actual trends on whether growth will increase or decrease under different climatic conditions. Relative humidity (RH) is used as it can be a major factor influencing plant growth. The cases used are outlined in Table 1.

Table 1 - Parameters Affecting Growth Functions

Case	Parameters	Growth
1	T+ P+ RH+	+
2	T+ P+ RH-	-
3	T+ P- RH-	-
4	T+ P- RH+	+
5	T- P+ RH-	-
6	T- P+ RH+	+-
7	T- P- RH+-	-

Whether the temperature and precipitation is determined to be increasing or decreasing is dependant on the climate normals. These are monthly average values of temperature and precipitation across Canada and the US for the years of 1971-2000. The deviation from these averages drives the growth equations.

Each case will have a different equation associated with it, increasing or decreasing the growth accordingly. Cases 1 and 2 can be intuitively understood in that if the temperature and precipitation show a positive deviation from the average the RH will decide on the outcome. A high RH will promote growth while low RH will inhibit growth. An example of such a growth function is presented on Figure 5.

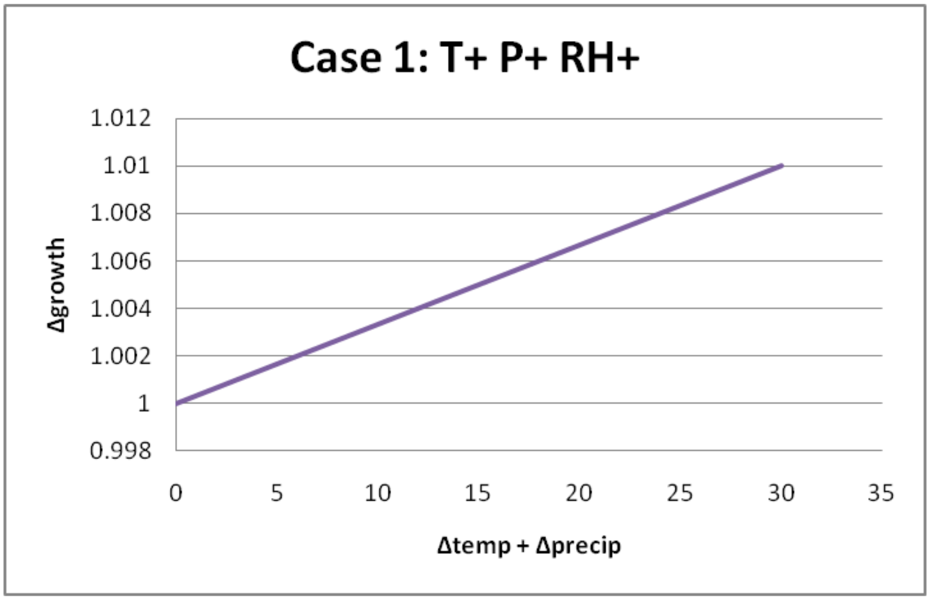

Figure 5 - Growth Function for Case 1, Increasing Growth

The degree at which the temperature and precipitation deviate from the climate normals determine how much change there is in growth. The Δgrowth on the y-axis is then multiplied to the interception capacity and in this case it may be increased to a maximum of 1% per year. More details on exactly how these equations are applied and at what point in the WATFLOOD code they are implemented are explained in the following sections.

2.2 Landcover Subroutines

All new landcover subroutines, coded in Fortran 95, are grouped in a single file containing a module that saves global variables, the main subroutine, and all supporting subroutines and functions. This section will give details on each subroutine and give an explanation on how the landcover equations are implemented into WATFLOOD. Flowcharts of the subroutines *Landcover_main* and *Landcover_incept* are included in Appendix 1.

2.2.1 Structure of *Landcover_main* and *Landcover_incept*

Landcover_main is the main subroutine that is called from WATFLOOD; all other subroutines are called from *Landcover_main*. This subroutine is called directly after the temperature and precipitation are both altered in accordance to the climate change scenario being simulated. This is to ensure that in the calculations of the deviations from the climate normals to determine change in growth, it is done so after climate change has taken place within the model. Information on the mechanics of the climate change subroutines can be found in (Slota, 2009).

Runoff in WATFLOOD is calculated on an hourly basis, if input data is of coarser resolution interpolating and disaggregation schemes are in place to accommodate this. Because of this fact *Landcover_main* takes the hourly gridded data forced into the model and calculates an average monthly value for temperature and precipitation. The climate normal for that month is then subtracted and depending on the RH a particular "case" is determined. The applicable equation is then applied to calculate a delta value to change the interception capacity for that month. An example of a function calculating delta values for varying degrees of deviation from the average temperature and precipitation is found on Figure 5. The interception capacity altering equations themselves are included in a separate subroutine *Landcover_incept* for ease of use and modification for future simulations. The maximum and minimum total long term change in interception capacity for each land class can be changed in *Landcover_incept*, as well as the equations themselves and their bounds (i.e. yearly maximum and minimum change).

2.2.2 Structure of *Landcover_locations*

Monthly averages of temperature and precipitation must be calculated to determine the deviation from the climate normals. However since the temperature and precipitation data is in a gridded format stored for every hour of a simulation, and the basins simulated can be quite large the computational effort required may be undesirable if every grid in the basin was used to calculate this average. To combat this only select grids are actually used in the calculation of the monthly averages, with the grids used determined by the locations of the gauges used for the raw temperature and precipitation data. Before WATFLOOD simulations are run, part of the pre-processing is spatially distributing the gauge data into gridded data across the basin. Therefore in the calculation of the monthly averages there is no benefit in using a larger sample size than the number of gauges – as long as the locations in the basin that are used for calculating the average are at the same locations as the gauges. *Landcover_locations* finds these locations for use in calculating the monthly averages and by doing so increases the computational efficiency of the model.

2.3 WATFLOOD Modelling Setup

2.3.1 Winnipeg River Basin Setup

Simulations were set up and ran with the Winnipeg River Basin (WRB). As indicated in Section 1.1 this basin is of particular importance to Manitoba Hydro as it produces a large amount of streamflow for power generation in the province of Manitoba. The WRB setup as viewed in EnSim™ is portrayed on Figure 6.

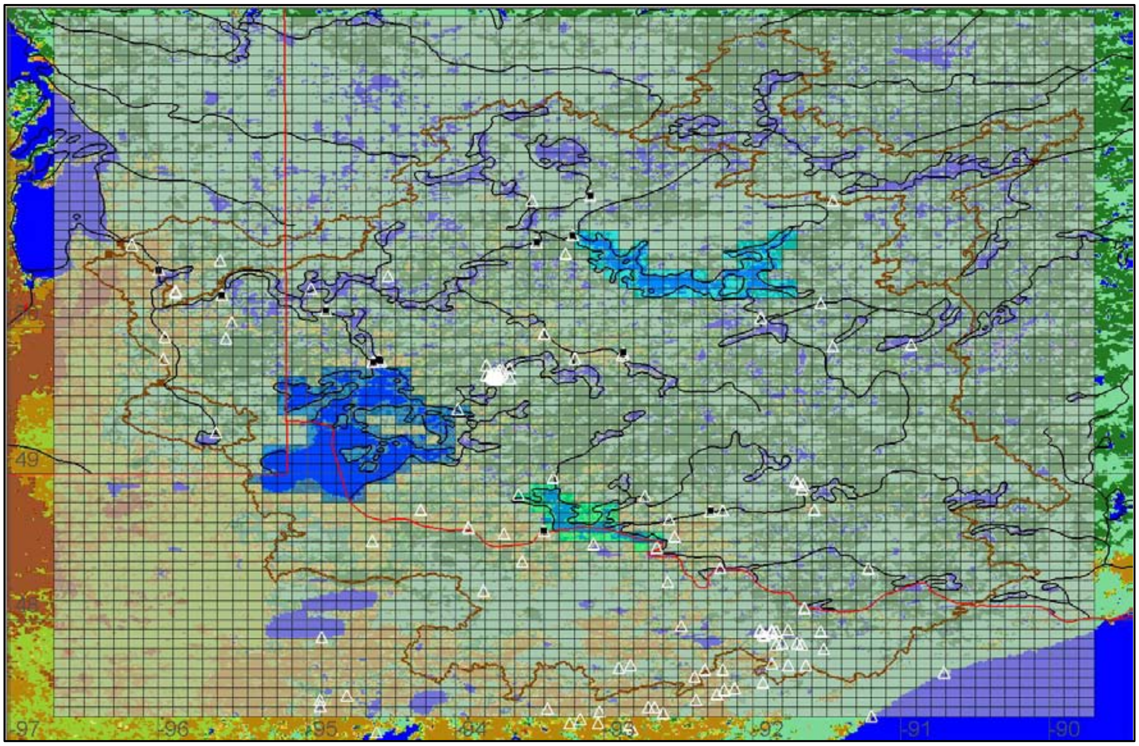

Figure 6 - WATFLOOD Setup of the WRB as viewed in EnSim™

In this representation the triangles represent flow gauge locations and the black squares river control structures. Each grid in the basin is 20km x 20km in size, with the total WRB amounting to 150,000 km^2 (Slota, 2009).

2.3.2 WATFLOOD Simulations

For certain output data such as interception evaporation from WATFLOOD a simulation grid can be selected to view the data from that grid. For this study the grid used for analysis is one near the Experimental Lakes Area near Kenora, Ontario. Its coordinates are 49^{o}39'36.34"N, 93^{o}43'41.02"W. This particular area was selected due to its familiarity with the author from previous field excursions and for its consistency in coniferous landcover. Figure 7 shows the landcover makeup for this grid as determined from areal photography.

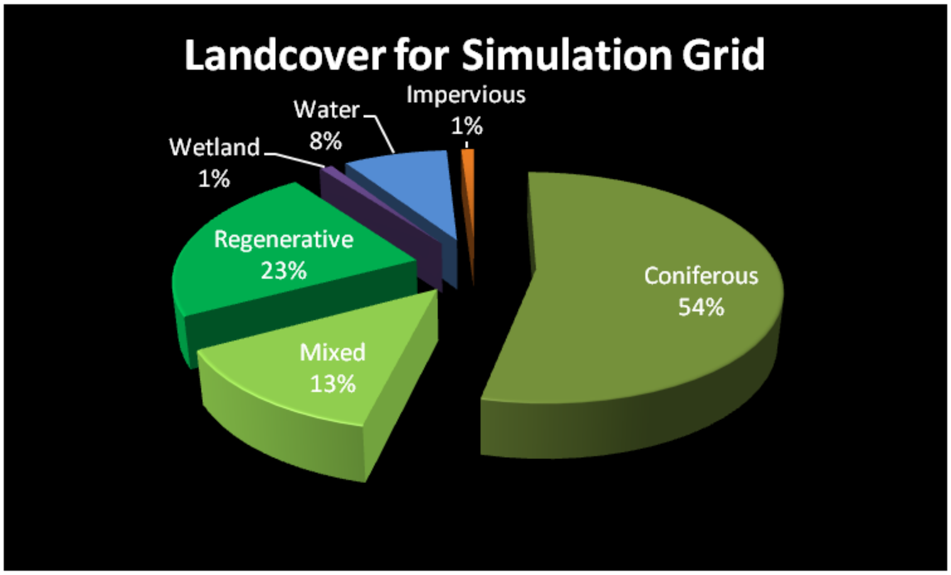

Figure 7 - Landcover Makeup in Simulation Grid near the ELA

Due to time constraints only one land class could be modelled and analyzed, and since coniferous forest is the dominant land class in this grid (as well as much of the northern areas of the WRB) it was chosen.

The climate change and landcover simulations were ran for 11 years spanning 1988-1999. Although IPCC recommends that climate change simulations should be run at a minimum of 30 years, the 11 year runs were deemed appropriate to capture the trends of the effects of climate change on landcover and to verify that the model is performing as expected. Data availability issues also become a problem with 30+ year simulations further making the shorter runs a necessity. However 5 years were also ran for model spin-up through the years of 1983-1988. This is to allow for clear views of the trends in the interception capacities over the course of the 11 year simulations.

3 Results and Discussion

3.1 WATFLOOD Simulation Results

For the 2080s time period, climate change simulations for the A2, B1, and A1b scenarios were conducted with and without the landcover modification scheme in place. Plots of the streamflow and of the differences in interception evaporation for the coniferous land class were then produced. Interception evaporation is the evaporation from the water in the interception storage of the hydrological cycle (Figure 3). It would be expected that with a growth increase and greater amount of water stored as interception, a greater amount of this water would be available for evaporation. It is in this way that the model was determined to be performing as expected.

3.1.1 Results: No Growth Restrictions

The following results are from running the landcover change simulations with no restrictions on maximum growth. The interception capacities changing through a simulation for each month are shown on Figures 8-10. These plots represent the A1b, B1, and A2 climate change scenarios respectively.

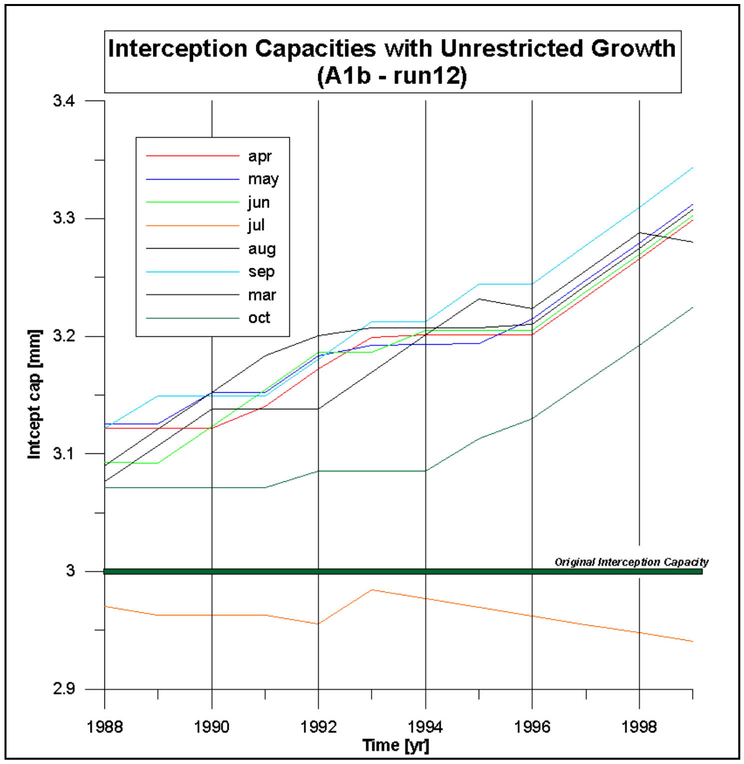

Figure 8 - Changing Interception Capacity with Time: Unrestricted Growth A1b Scenario

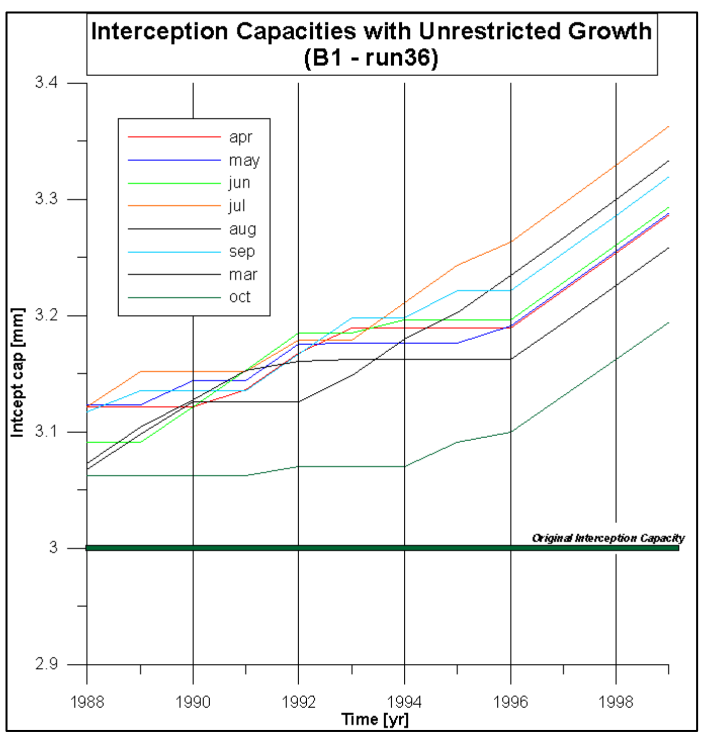

Figure 9 - Changing Interception Capacity with Time: Unrestricted Growth B1 Scenario

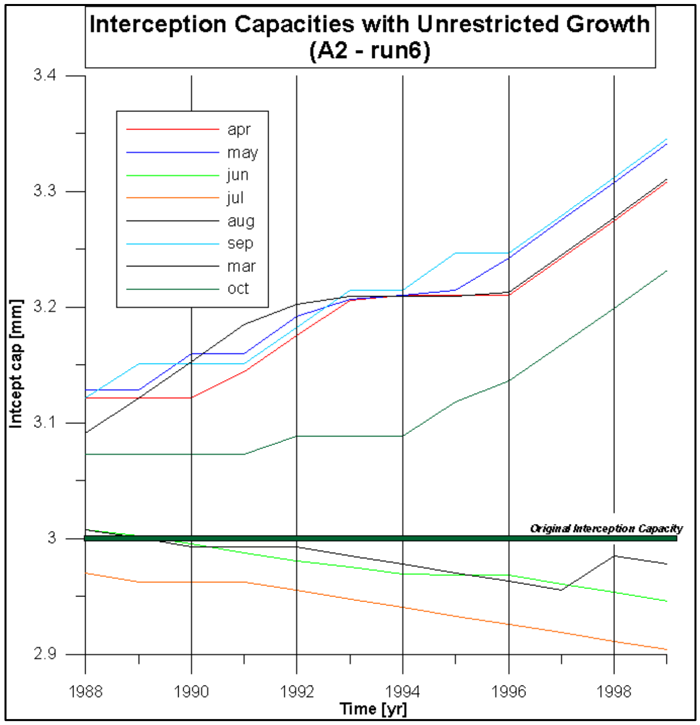

Figure 10 - Changing Interception Capacity with Time: Unrestricted Growth A2 Scenario

The resulting difference in interception evaporation for the coniferous land class between climate change runs with the landcover change scheme and climate change runs with no landcover change scheme is shown below on Figure 11. All three climate change scenarios are simulated with different initial conditions. Only the maximum and minimum results are shown, indicating a possible range predicted by each climate change scenario.

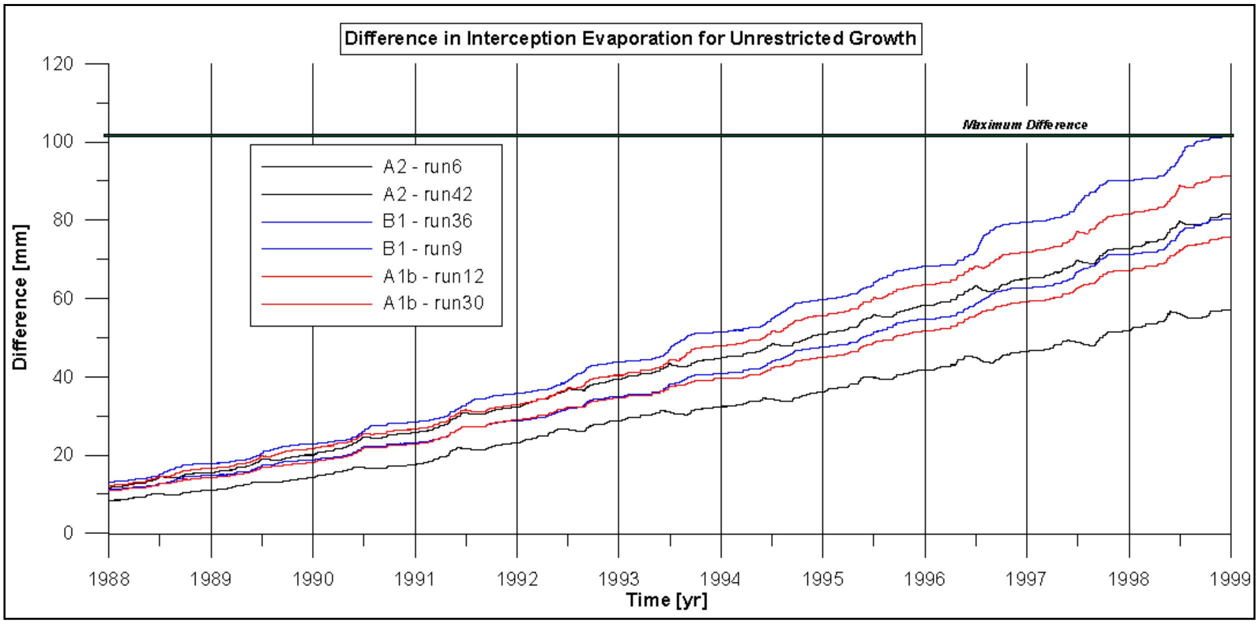

Figure 11 - Difference in Interception Evaporation for Unrestricted Growth

3.1.2 Results: Growth Restrictions

The simulations from Section 3.1.1 were conduced again in the exact same manner with the only change being that the maximum interception capacity of the coniferous land class being fixed at 3.175 mm. This value was chosen by looking at the unrestricted growth plots on Figures 8-10 and deciding on a value that would have significant impacts on the simulation results. Figures 12 and 13 show the results of the simulations with restricted growth.

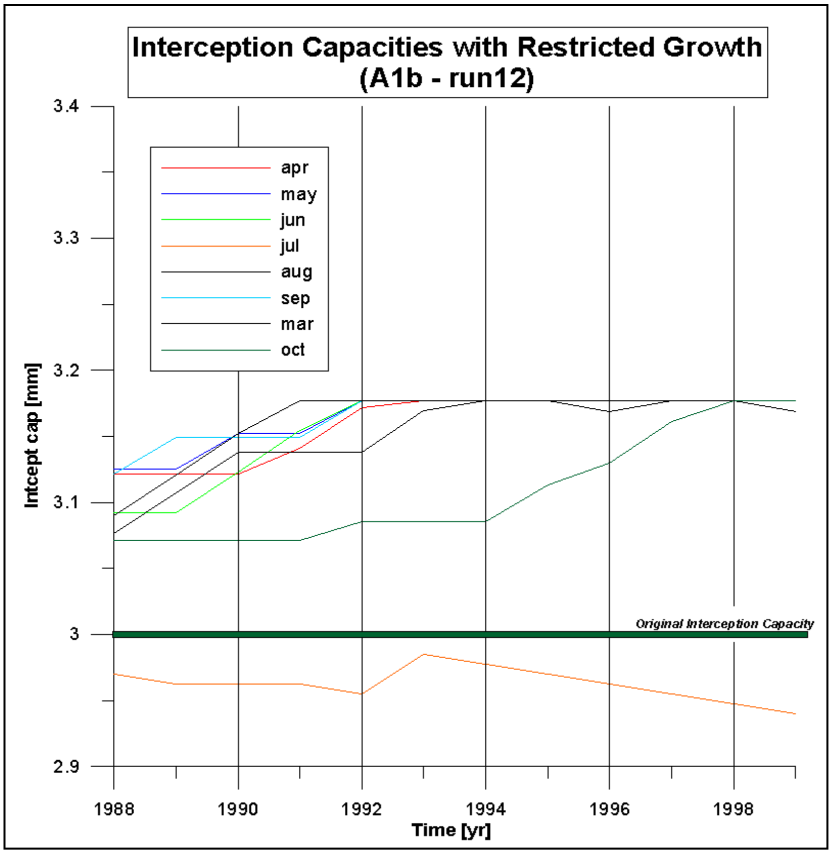

Figure 12 - Changing Interception Capacity with Time: Restricted Growth

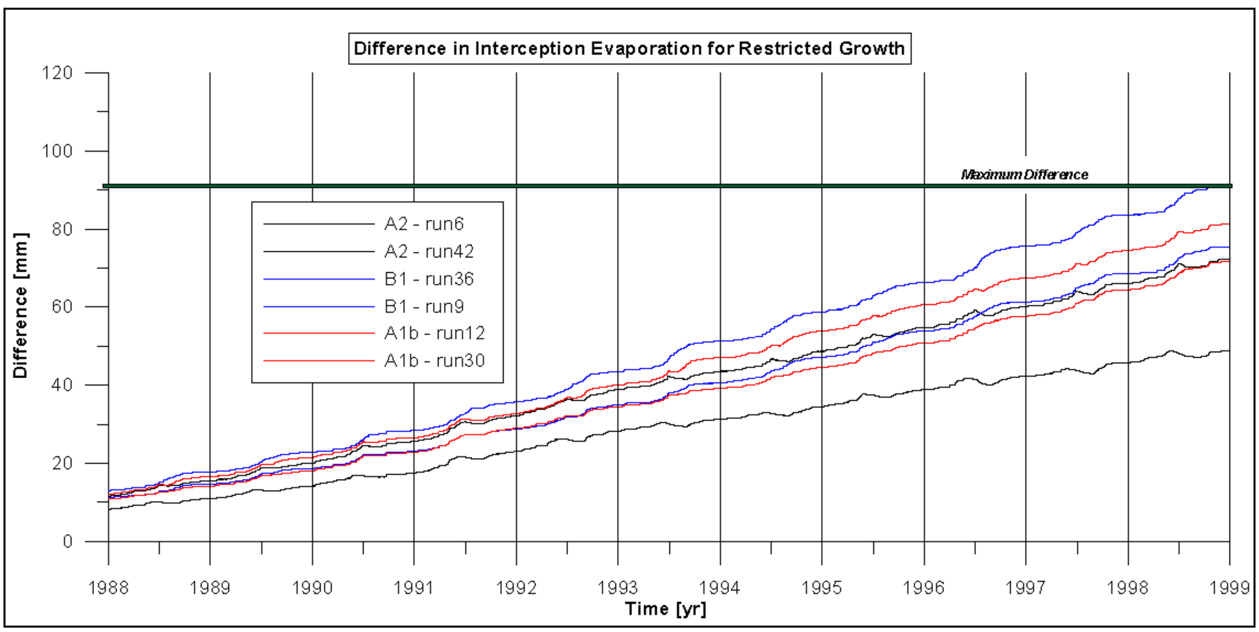

Figure 13 - Difference in Interception Evaporation for Restricted Growth

3.1.3 Results: Streamflow

Plots of the streamflow predicted from WATFLOOD are presented on Figures 14 and 15. Figure 15 is a zoomed in portion of July and August of 1990 shown for clarity. These are from the simulations showed in Section 3.1.1 with unrestricted growth, as well as a baseline simulation with no climate change scenarios ran at all.

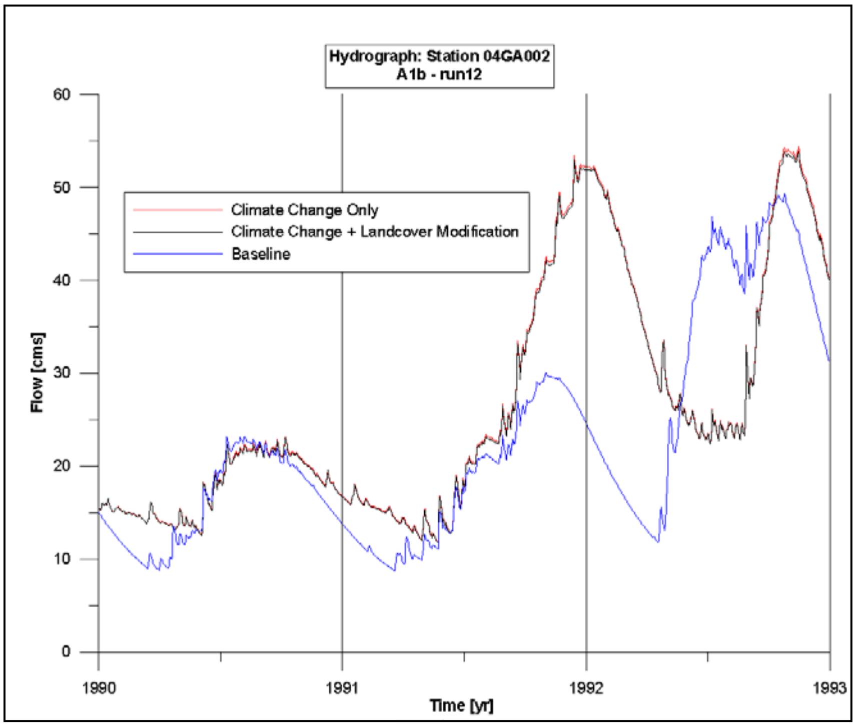

Figure 14 - Hydrographs as Output by WATFLOOD: 1990 - 1993

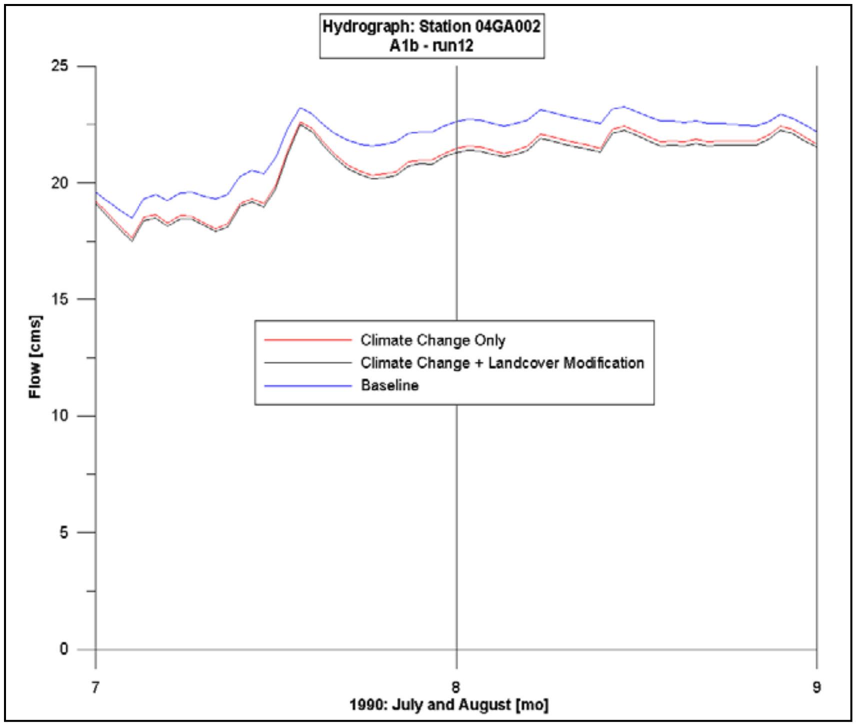

Figure 15 - Hydrographs as Output by WATFLOOD: July - August 1990

3.2 Discussion

Results from the interception evaporation plots show expected output from the model. The changes in interception capacity over time for the B1 scenario show increasing growth across all months on Figure 9. These effects can directly be seen with the difference in interception evaporation graph on Figure 11. The constant increasing growth across the entire simulation results in an ever increasing evaporation for the B1 scenario. However the month of July for the A1b scenario shows a decreasing trend. This is evident in the simulation in that every year there is a decreasing spike in the evaporation due to this lower interception, however with an increasing overall trend due to the overall increase in growth over the years. The A2 scenario also has some decreasing growth however over more months than the A1b. In response to this the yearly decreasing trend in evaporation is longer in duration – still generally increasing however due to the overall increase in growth with this scenario.

The simulations ran on restricted growth conditions showed very similar trends in the interception evaporation plots. The main difference to note is that although the trends are the same, the total difference in interception evaporation is lower as indicated by the green bar on Figure 13. This is due to the fact that the interception capacity peaks and stops increasing through the simulation. The difference in interception evaporation increases because the interception capacity is still higher than before resulting in increased evaporation, it's just not further increased every year.

The hydrographs on Figures 14 and 15 present three plots: Climate change with landcover modification, climate change without landcover modification, and a baseline with no climate change. Worth noting is the peak flows occurring in the winter months with the advent of climate change, consistent with the conclusions from a study by (Slota, 2009). These are 2080s runs and predict far into the future, however this may have major implications for Manitoba Hydro. The hydrographs from the simulations with climate change and landcover are slightly lower than the runs solely running climate change. This is expected in that with a greater amount of water being stored and evaporated as interception, less water would fall to the ground and be produced as runoff.

These results show that the landcover model performs as expected in respect to evaporation and streamflow as a result of modifying landcover growth with climate change scenarios.

4 Conclusions and Recommendations

The landcover modification scheme implemented in this study is the first step in fully enabling WATFLOOD in accounting for landcover changes induced by climate change scenarios. The focus of this study is modifying the growth of land classes with climate change scenarios and results were produced describing the changes in interception evaporation and runoff. All of these aspects of the simulation performed as expected increasing the confidence of the model output.

However there is much more work to be done in the landcover modification scheme and from the completion of this study the following recommendations can be made for further research and development of the model:

- Include a randomized component to the interception capacity modification equations. This is to accommodate random events that may have a significant impact on the growth in the basin. For example seasonal extremes in warm/cool temperatures or high/low levels of precipitation could be accounted for in the model.
- Investigate and apply equations into the model to modify the growth of all land classes. In this study coniferous forest was the only land class that was included in the landcover modification scheme. However all land classes are included in the landcover portion of the source code, the equations just need to be entered. The focus would be to determine the growth response of each landcover type to changes in temperature and precipitation

as predicted from climate change scenarios and run simulations to test the hydrological response to these changes.

- A critical step in developing WATFLOOD to be fully enabled for climate induced changes in landcover would be including the changes in the proportions of land cover classes in each grid as a result of climate change scenarios. Using the example in Section 1.3.2 with the northward shifting of the coniferous-deciduous forest boundary; this effect could be implemented in such a fashion of increasing or decreasing the proportions of land cover classes for grids in the watershed.

The landcover modification scheme developed for WATFLOOD in this study is the first to implement such changes induced by climate change scenarios in a hydrological model. Such improvements are vital to predicting the hydrological responses to climate change in that the changes in the resultant landcover affect the changes in streamflow and ultimately power generation due to climate change.

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Appendix 1 – Subroutine Flowcharts

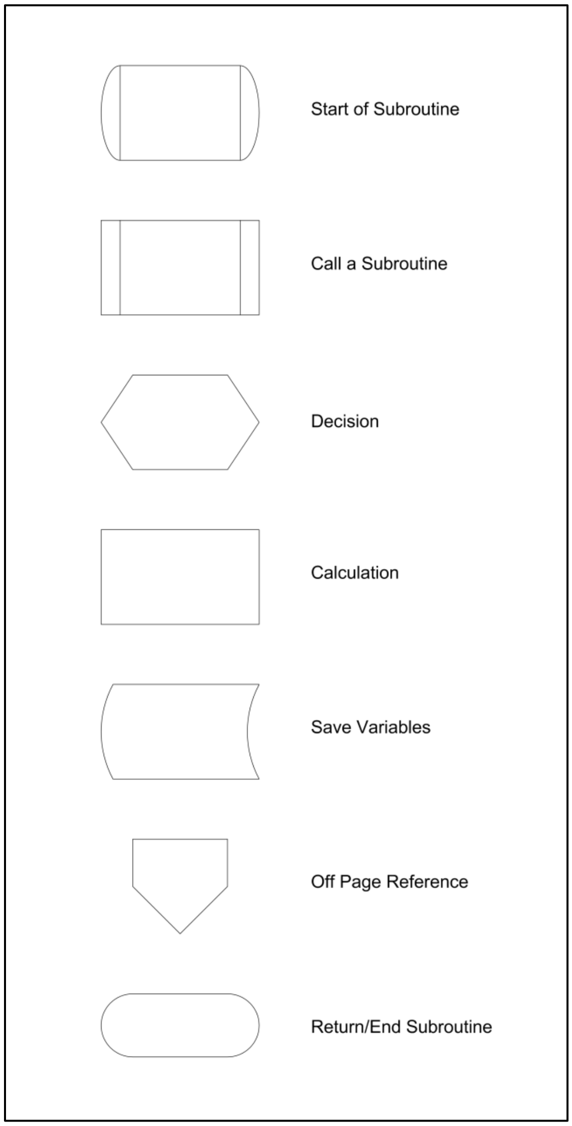
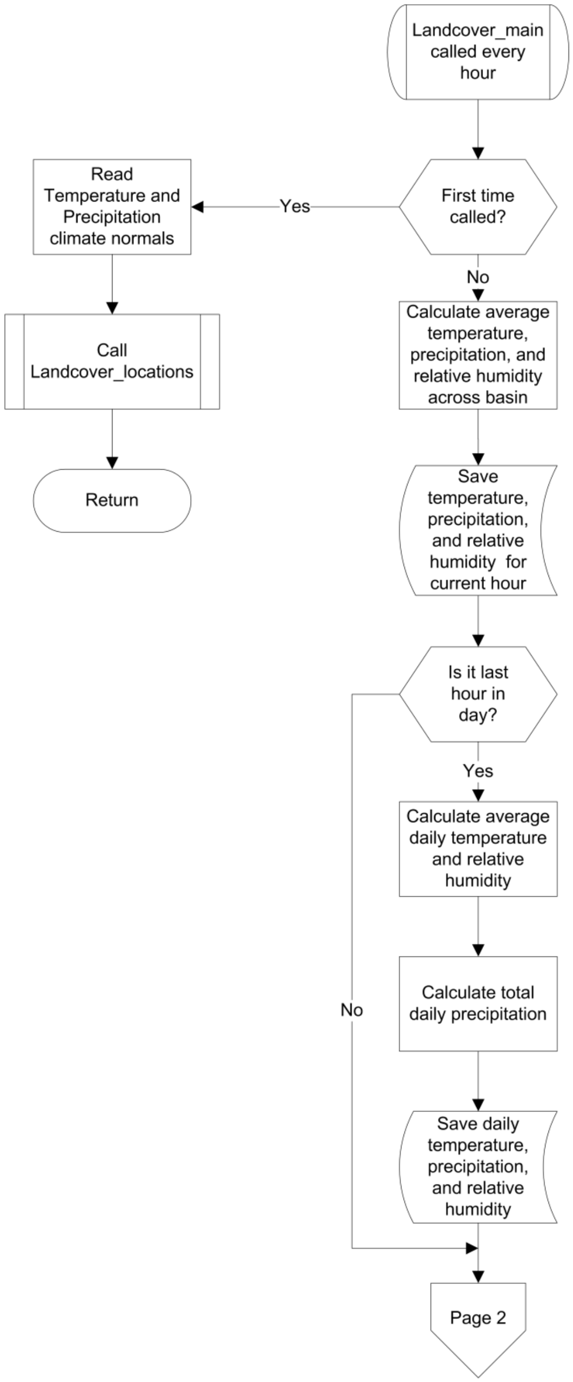
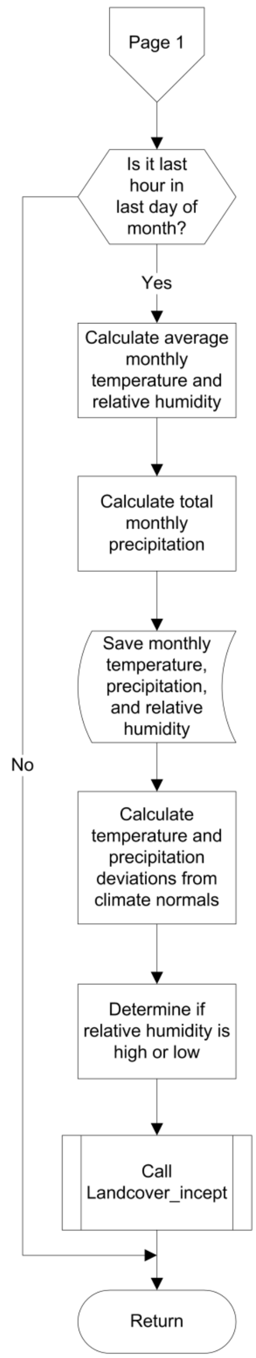


Figure 16 - Flowchart Legend

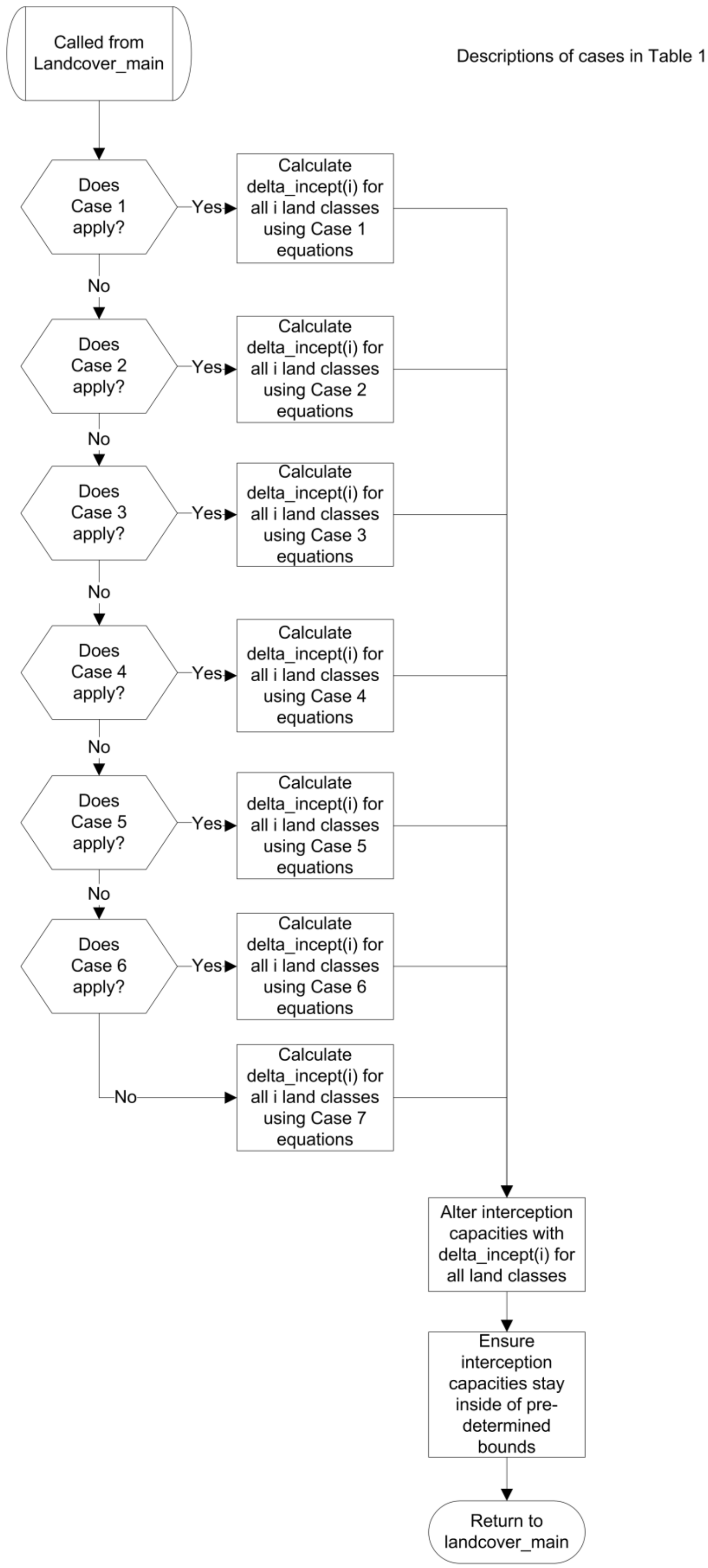
***Landcover_main* Subroutine**



Landcover_main Subroutine



Landcover_incept Subroutine



Appendix 2 – Input Files

The following are two example parameter files that are of required input for the climate change and landcover modification scheme. The top file contains temperature data and the bottom precipitation. The first line contains delta values for temperature or precipitation as predicted by GCMs, and the second are the climate normals for use in the landcover modification scheme.

clim_precip.par

```
1.24530 1.52460 1.23760 1.36130 1.38720 0.96626 1.10960 1.02680 0.93303 1.38360 1.20030 1.13260
24.26 18.57 27.27 35.33 62.95 99.80 93.77 86.83 78.99 54.40 38.03 23.82
```

clim_temp.par

```
5.41660 4.99870 4.87520 2.41210 2.71440 2.60950 3.68890 2.84700 3.73490 3.27200 1.58410 4.51860
-17.36 -13.03 -5.74 3.40 11.34 16.17 18.84 17.54 11.59 5.02 -4.82 -13.90
```