HYDROLOGIC COMPARISONS AND MODEL SIMULATIONS OF SUBARCTIC WATERSHEDS CONTAINING CONTINUOUS AND DISCONTINUOUS PERMAFROST, SEWARD PENINSULA, ALASKA

by

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A
THESIS

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ABSTRACT

Mauze Gulch (4.9 km^2), and Niagara Creek (6.5 km^2), located near Kougarok, Alaska and Melsing Creek (80.6 km^2), and Clyde's Gulch (2 km^2), located near Council, Alaska were studied to quantify the hydrologic response of these watersheds. They have been studied extensively as part of the NSF Arctic Transitions in the Land-Atmosphere System (ATLAS) study. These watersheds demonstrate a progression from a continental subarctic to a marine moderated subarctic environment. Each contains varying proportions of permafrost. Mauze Gulch and Niagara Creek are underlain by continuous, warm, thin permafrost (~15-50m thick). Melsing Creek and Clyde's Gulch are underlain by discontinuous permafrost.

The Swedish HBV-96 model was applied to these watersheds. The model requires minimal input of meteorological data (temperature and precipitation) to generate hydrographs. Examining the basic stream hydrology showed that differences in hydrologic response based on permafrost distribution can be identified. By changing parameters, such as field capacity and the percolation to the groundwater, it is possible to reflect physical differences between watersheds using the model. Results of this study were compared with previously studied basins in Alaska. Comparisons showed that model parameters can be used to distinguish differences in hydrologic response in basins with varying amounts of permafrost.

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Thanks to the National Science Foundation who provided funding for this project.

I am very grateful for the support of my family.

INTRODUCTION

Background

These studies are undertaken as a part of a National Science Foundation program, the Arctic Transitions in the Land-Atmosphere System study (ATLAS). The goal of the ATLAS study is "to determine the geographical patterns and controls over the climate-land surface exchange (mass and energy) and to develop reasonable scenarios of future change in the arctic system" (LAII, 1998). This is an extensive study that aims to bring researchers together and couple field and modeling studies. This thesis focuses on comparing the physical hydrology, measured and observed in the field, with computer modeling of the hydrology of the same basins. The ATLAS project incorporates sites from the North Slope, Seward Peninsula, and Russia but the data collected and used in this study are only from basins on the Seward Peninsula at Kougarok and Council (Figure 1).

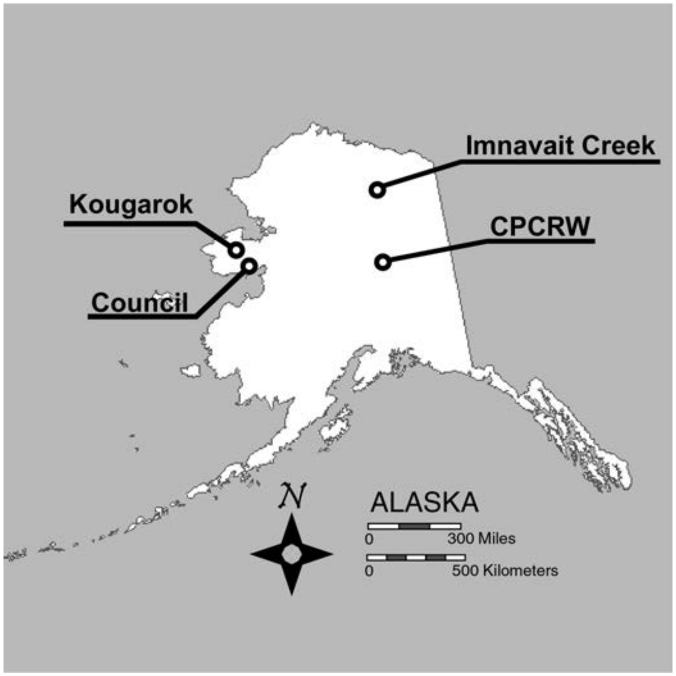

Figure 1. Map of Alaska showing the study areas.

The sites in the ATLAS study were chosen because they represent a progression of climatic regimes from cold arctic to a warmer subarctic climate. The Seward Peninsula represents a climate that is warmer than that of the North Slope, which was the focus of earlier research, but cooler than more temperate regions that do not contain permafrost. The climatic regime of the Seward Peninsula is a proxy for what the North Slope may become under a warming scenario. By studying the Seward Peninsula, researchers are hoping to gain insight into potential changes in the natural systems and to develop the ability to quantify the impacts of global warming in arctic regions.

Scientists may not agree on the magnitude of change but there is agreement that the earth is changing due to the increase of carbon dioxide in the atmosphere both from natural and anthropogenic sources. "Despite skeptical voices, most experts accept the risks of climate change as a serious problem that requires action now" (Hengeveld, 2002). Research of carbon isotopes suggest that the long term increase in CO_2 in the atmosphere is the result of the burning of fossil fuels (Hengeveld, 2002). The severity of global warming is still being argued but most scientists agree that the potential impacts may be great. This thesis does not aim to debate the occurrence of global warming, but rather to look into the potential impacts that warming may have.

The hydrologic cycle is a key component of climate dynamics. An important aspect of understanding the exchanges of energy between the land and atmosphere is the hydrology. Water represents a large source of energy exchange via transfer of latent heat and sensible heat. A change in the climate will affect the water balance across the earth. This study aims to take a step towards understanding the major changes that may occur in the Arctic if the climate warms enough to start melting the permafrost that currently underlies much of northern Alaska.

"Among the most fundamental effects of climate change are intensification and disruption of the water cycle" (Backlund et al., 1997). On a global level, droughts are likely to become more severe in parts of the world as are floods in other parts. A large concern is the effect on the fresh water supply in places where water is already scarce. The results from global circulation models differ considerably when it comes to predicting precipitation, but the overall tendency is an increase in precipitation (Vehviläinen and Lohvansuu, 1991) with significant increases in the mid to high latitudes (Hengeveld, 2002). Changes in the water cycle produce a chain reaction that will trigger a change in vegetation. Changes in temperature of 0.1°C or more per decade may cause adaptation problems to forests (Vehviläinen and Lohvansuu, 1991). Soil moisture is an important condition that governs the type of vegetation that grows in an area. Within the Arctic, warmer climates will favor the emergence of new plant species, primarily as shrub species (Hengeveld, 2002; Sturm et al., 2001).

Permafrost underlies approximately 24% of the exposed land area in the Northern Hemisphere (Romanovsky et al., 2002) making it a significant proportion of the land mass and a crucial component to study and understand. In the Arctic, it is predicted that as a climate warms, the active layer will deepen and permafrost will gradually disappear. The changes invoked by the degradation of permafrost will have impacts on the landscape, ecosystems, and the social and economic structure (Romanovsky et al., 2002). Studies have been done that show that the temperature of permafrost in Arctic Alaska has increases by 2-4°C over the last century (Lachenbruch and Marshall, 1986). Melting permafrost would have huge impacts on the hydrology in the Arctic and Subarctic where watersheds are currently underlain by permafrost. As the permafrost melts, the active layer will deepen and taliks may be formed creating a larger zone available for water storage. In addition, water will be released from the permafrost when it melts in ice-rich areas. A possible consequence floods may become less severe because water will be able to move vertically through the active layer instead of being confined in the zone above permafrost (Kane, 1997). There would be a major impact on existing infrastructure in affected areas. Degradation of permafrost in arctic systems may have negative impacts on existing infrastructure. Human disturbances to permafrost will be enhanced in a warming climate making it necessary to incorporate climate change in the design of future developments (Romanovsky et al., 2002). As permafrost starts to melt, the land responds in various ways. Thermokarsts are a common result of melting permafrost that changes the landscape and changes the hydrology of the system.

The Arctic plays an important role in the global climate and changes in the Arctic can significantly impact the climate elsewhere (Kane, 1997). The degradation of permafrost may be a primary concern because of the sensitivity of soil carbon fluxes to temperature change. The Alaska tundra changed from a carbon sink to a carbon source in the 1980's due to regional warming and future warming is likely to enhance this cycle (Hengeveld, 2002). As many studies have shown, carbon dioxide is a main greenhouse gas and scientists are trying to understand what impact the release may have on the global climate. For this reason, the Arctic is important in understanding the global carbon balance. Many global circulation models (GCMs) have forecast that the warming in the Arctic will be more severe than other areas of the world (Vörösmarty et al., 2002). In these same studies it is predicted that, in general, precipitation will increase at high latitudes.

This thesis is a summary of the hydrology of four watersheds on the Seward Peninsula and a comparison of these watersheds, which represent different subarctic environments. Looking at existing watersheds that have varying amounts of permafrost may provide insight into the different characteristics these watersheds exhibit and may help to predict what may happen in a warming scenario. This research primarily aims to apply a conceptual runoff model to watersheds that display different hydrological processes. The basic hydrology of each basin was studied and differences between the watersheds were analyzed and a conceptual model was executed and evaluated for its applicability to these watersheds. The HBV-96 model was chosen because it has been proven successful for predicting runoff in watersheds in Alaska (Hinzman and Kane, 1991; Sand and Kane, 1986; Knudson and Hinzman 2000).

LITERATURE REVIEW

Arctic Hydrology

Numerous studies have concluded that permafrost has a significant influence on streamflow characteristics (Church, 1974; Hinzman et al., 1993; McNamara et al., 1997; Woo and Steer., 1983). Drainage network development in the Arctic is immature because erosion is limited when permafrost is present (McNamara et al., 1999). This is extremely important when considering the impacts a changing climate may have. With the loss of permafrost the potential is increased for erosion of unfrozen streambeds and banks resulting in an increase in the amount of sediment in a stream. This can affect aquatic and marine ecology.

Several stream processes are affected by permafrost. The presence of permafrost is a large control on the runoff response time. This is because of a shallow active layer, the seasonally thawed surface layer above permafrost, which is confined on the bottom by a frozen layer. Permafrost accelerates the initiation of runoff (McNamara et al., 1998). Arctic watersheds have fast response times because vegetation in these areas tends to be sparse (Church, 1974). Permafrost limits the amount of soil water percolation and the amount of subsurface storage of water (Vörösmarty et al. 2001). Although the response times are much quicker in permafrost basins, the recession time of the stream has been shown to be longer than in basins without permafrost (Dingman, 1973; McNamara, 1998.)

Studies have shown that frozen soils are not impermeable (Kane and Stein, 1983) and thus frozen ground should be thought of as a soil of low hydraulic conductivity. Frozen soils contain ice, soil and unfrozen water that may be mobile. In most cases frozen ground can be thought of as a confining bed of very low hydraulic conductivity. Ice-rich frozen soils may be considered nearly impermeable.

Woo (1986) summarizes the classification of streams in northern rivers based on dominant characteristic runoff patterns. There are four main types described: nival regime, proglacial regime, wetland regime, and spring-fed regime. Nival regime rivers are the most common in

Alaska, snowmelt floods dominate these streams. The proglacial is dominated glacier fed rivers. The wetland regime (muskeg regime) is typified by poorly drained tundra streams. The last is the spring-fed regime that has primary flow from groundwater and is usually associated with carbonate rocks in discontinuous permafrost basins.

Snow accumulates over a long period in Alaska, typically 8-9 months, and is released within a short amount of time (usually two weeks or less) (McNamara, 1998). Continuous heat loss in the winter leads to complete freezing of the active layer (Woo, 1983). A sharp rise to peak flow early in snowmelt distinguishes watersheds at high latitudes from temperate regions. The snowpack accumulation and ablation is often the main hydrologic event of the year (Kane and Hinzman, 1988; McNamara et al., 1998; Woo, 1986). The spring thaw and runoff are proportionally more important in permafrost basins than it is in more temperate regions when studying the hydrologic cycle (Ambler, 1974). The intensity of the winter temperatures combined with the amount of snow and ice in a river channel intensifies the freeze-up and break-up processes when compared to rivers in more temperate climates (Woo, 1986).

During the long subarctic winter, there is almost no snowmelt contributing to runoff. Rapid melt due to high radiation is characteristic of the Arctic and snow can melt at rates of 25 mm/day or more of water equivalent (Woo, 1983). Kane et al. (1991) showed that runoff typically did not occur until 50% or more of the snowpack has ablated. The effect of snow storage is the most important feature of the hydrological cycle everywhere in the north (Church, 1974). Approximately 50-66% of the initial water content in the snowpack contributed to direct runoff in a headwater basin in the Arctic (Kane et al., 1991).

Permafrost is a stratum creating an impermeable lower boundary of the watershed (Kane et al., 2000), making it an effective aquitard near the surface. Water move through permafrost in areas where permafrost is discontinuous, where taliks occur, and below sufficiently large water bodies. In regions of thick continuous permafrost there is little possibility of groundwater continuing to provide baseflow in winter, except in remarkable circumstances such as areas where there are large springs on the North Slope of Alaska. Taliks may exist under the frozen channel bed (Church, 1974). Groundwater can emerge in springs or seep through river and lakebeds (Kane and Slaughter, 1973). Church described the flow in watersheds as a “surface/soil phenomenon”. The runoff in these basins, where the permafrost is continuous, is the result of seasonal rainfall, snowmelt, or flow through the active layer.

There are many obstacles to overcome when doing fieldwork in the Arctic. Woo, 1988 lists some of the main complications of trying to carry out water balance calculations in remote regions. He states that good water balance calculations require good measurements of precipitation, runoff, soil moisture, and evapotranspiration. The latter is the most difficult to obtain and in many studies evapotranspiration is calculated as a residual term in water balance calculations such as a study by Kane et al. (1990).

The Arctic can be described as a desert when looking at the amount of total precipitation is receives during the year. Kane et al., 2000 reports a maximum of 42.2 cm of total precipitation falling in the Imnavait Creek watershed on the North Slope of Alaska. Several water balance studies have been done in the Arctic (Lilly et al.,1998; Woo et al., 1983; Kane et al. 2000). Woo reported a six year annual average of total runoff/total precipitation ratio of 0.83 near Resolute Canada. A four year annual average total runoff/total precipitation ratios in Imnavait Creek on the North Slope of Alaska =0.53 (Kane et al., 2000). Woo (1986) reported typical total runoff/total precipitation values of 0.7 to 0.8. McNamara et al. (1998) found an average of 0.5 in basins on the North Slope. This is compared to a global ratio of 0.36 from Baumgartner and Reichel, (1975).

When making water balance calculations it has been found that soil moisture values are similar from year to year just before freeze-up due to consistent and persistent autumn rainfall saturating the active layer (Lilly et al., 1998). Annual water balance calculations in the Arctic have been simplified based on the previous findings. It has been assumed that there is no net change in water stored in the active layer from year to year (Lilly et al. 1998, Woo et al. 1983).

Recession constants are key characteristics when describing the hydrology of a basin, as it reflects physical features of the watershed (Kane et al. 2003). One major study was done by Holtan and Overton (1963). In temperate regions they found that the recession constant tends to increase with basin size. Dingman (1971) did a study in a discontinuous permafrost site, Glenn Creek, Alaska. In his study, he found that recession constants in permafrost basins were much higher than basins of comparable size in temperate regions. Findings were also substantiated by McNamara et al. (1998) who stated that permafrost accelerates the initiation of runoff and reduces the baseflow contribution. This implies that water drains much more slowly from a basin that contains permafrost than basins that are permafrost free. Dingman reported an average recession time of 39.2 hours in a 1.8 km^2 basin with approximately 50% permafrost. McNamara et al. (1998) studied continuous permafrost basins and found that a 2.2 km^2 basin had an average recession time of 30.2 hr. in Imnavait Creek. A clear explanation of this phenomenon was given by Kane et al. (2003), where is has been stated that "permafrost limits subsurface storage and water is retained in a shallow active layer where pathways are limited to evapotranspiration and runoff."

Site History

Primary research on the presence of permafrost on the Seward Peninsula has been done by Hopkins and Sigafoos (1951). In these studies the Seward Peninsula is separated into northern and southern regions. The northern region is described as consisting of ground that is perennially frozen almost everywhere with a few exceptions; beneath lakes and hot springs and under the channels of perennial streams. The thickness of the permafrost was stated as being between 4.6 and 79 m. Thaw depths were between 0.3 and 3 m at the time of his studies. The groundwater in the northern region is most commonly found in the gravels beneath large streams. Limited groundwater may also be found in upland valleys beneath stream channels, at the interface between bedrock and gravel.

The southern Seward Peninsula is described as being mostly perennially frozen but the southern part of the peninsula contains thawed zones that are considerably more abundant than in the northern part of the peninsula. The frozen ground in this part of the peninsula was found to be from a meter thick to 110 m thick with 30-60 m thickness being typical. The active layer at the time of this study was estimated to be between .3 and 3 m. As expected, the unfrozen zone are much more common in smaller streams and under floodplains than they are in the northern part. Groundwater is obviously much more abundant due to the discontinuous nature of the permafrost, that allows subsurface infiltration, and an increase in precipitation in the southern areas.

Rainfall/Runoff Models

Hydrological models are generally used for three main reasons; to simulate natural discharge, operational forecasting, and prediction of effects of future physical changes in catchments (Bergström, 1976). Bergström defines a conceptual model as a model, which considers the physical characteristics of a basin. This is in contrast to a black box model, which does not take into account the physical characteristics of a basin. The HBV model used in this study is said to be a compromise between the two above-mentioned models. The model is constructed around the physical characteristics of a basin but there are parts of the model that are empirical.

There are several factors to consider when assessing accuracy of a model. Melching et al. (1990) listed four sources of uncertainty; natural randomness, data, model parameters, and model structure. Natural randomness refers to the uncertainty associated with spatial and temporal variation in the natural system and their effects on the physical processes being modeled. The accuracy of data includes errors in data collection, for example the wind affecting a rain gage. Also included is the gaging network and its adequacy, and any errors in transmitting the data. The model structure uncertainty is how well a model can simulate a watersheds true processes. Melching et al. (1990) notes that the uncertainty of a model would be easy to determine if the natural system were ideal and not represented by estimated values of the true system. Models are validated not on 'true' values, but estimated values that have been collected in the field, which include their own error.

Previous Studies with the HBV Model

The HBV model has been written in many forms (Vehviläinen and Lohvansuu, 1991). It has been widely used and adapted for specific uses. It has been reported that the HBV model is widely used in Finland (over 50 applications). It has been tested and used in many areas around the world including Alaska (Hinzman and Kane, 1992; Kane and Sand, 1986), South America (Häggström et al., 1988) and Sweden (Lindström et al., 1997) just to name a range of global applications. Its wide range of applicability is attributed to its simple structure (Figure 2).

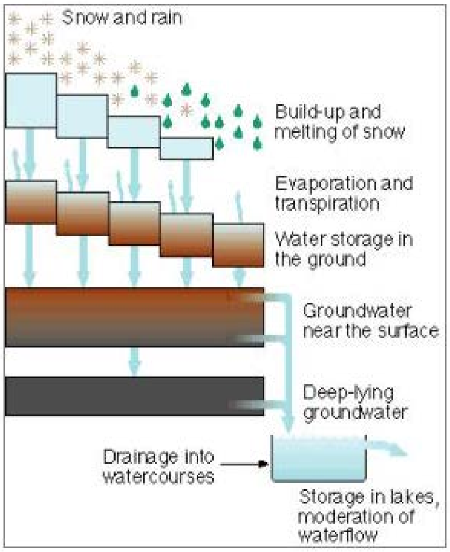

Figure 2. HBV-96 Model structure, from SMHI (1996).

Several studies have been done using models to predict responses to changing climates. One study in Finland focused on how climate would affect discharge and snow cover. Some of the simulations in this study used the HBV model (Vehviläinen and Lohvansuu, 1991) to simulate the runoff of the basins. Twelve watersheds were studied for their response to climate change. The study predicted that the mean runoff would increase by 20-50% during the winter in the study basins and winter snow water equivalent (SWE) will decrease. This is the result of shorter winters and shorter time period for snow to accumulate. In addition, peak flows in spring would decrease considerably due to decrease in SWE. The increase in precipitation is counter-acted by increase in evaporation during the summer months and very little difference was seen in summer discharge. A study in Alaska done by Hinzman and Kane (1992) used the HBV model to study the effects a 4°C temperature increase would have on the hydrologic regime in a watershed in the Alaskan Arctic. They adjusted the thickness of the active layer to account for an increase in temperature. It was found that snow ablation would occur earlier, snow deposition would occur later in the fall, cumulative evaporation would increase and cumulative runoff would decrease.

Häggström et al. (1988) reported that a river with a slow response is easier to forecast than a river with a quick response to rainfall or snowmelt. This is important to consider when choosing watersheds that the model will be applied to. Small watersheds in the Arctic have quick response times making it difficult to apply models that are better suited for larger watersheds with more stable hydrology. Hinzman and Kane (1991) observed that the variability from year to year in the hydrology made it difficult to calibrate the HBV model for the watershed but concluded that the model structure was flexible enough to adequately simulate the hydrology for any given year.

Seibert (1997) discussed the uncertainty associated with estimating the parameters in the HBV model. He concludes that it is difficult to find one parameter set that is unique to a basin although this is what most researchers strive to do. Again, this is especially problematic in watersheds that have quick response times to rainfall and snowmelt. One main study by Braun and Renner (1992) has been done using the HBV model to relate basin hydrology to model parameters. This study was done using five watersheds in Switzerland. In this study it was found that "no conclusive relationships between parameter values and basin characteristics could be found". One reason that this study may not have been successful is that the sample was too small. Another reason is that this model may not be suited to relate parameter values. Still a more probable reason is that the watersheds may not be dissimilar enough in character for the model to reflect the differences.

STUDY AREA

Permafrost

The extent and thickness of permafrost is difficult to quantify. Depending on the vegetation cover, aspect of the slope, regional climate, and grade of the slope, it can vary greatly over a small area. The Seward Peninsula, especially the southern part, contains discontinuous permafrost, making it a difficult place to accurately determine the permafrost distribution in the study areas.

The only conclusive method to determine the extent and thickness of permafrost is to drill several sites and install a network of thermistors. This is an extremely expensive undertaking and was not the prime focus of this project. It is fortunate that researchers were able to drill several holes on the Council area and one boring near the Kougarok watersheds. Geophysical surveys, such as ground penetrating radar (GPR) and direct current resistivity, can be useful tools when determining thickness and extent of permafrost (Harada and Yoshikowa, 1996). When performing GPR surveys, it is crucial to have physical data such as well logs to confirm the results from the geophysical methods. When determining the extent of the permafrost in this study, observations of such features as springs were used when trying to determine the permafrost distribution.

The Mauze Gulch and Niagara Creek watersheds are considered continuous permafrost but relatively thin. This equates to a thickness of 20 m or less. There are two sources of drill data coupled with observations that lead to this hypothesis. One hole was drilled south of Kougarok, about 30 km, (Yoshikowa and Hinzman, 2000) and was found to be about 15-20 m thick. Another hole was drilled, about 40 km northeast of Kougarok, to a depth of 46 meters Permafrost was encountered to a depth of 20 m (Hopkins, 1963). The presence of a small spring in Mauze Gulch and observed aufeis and frost blisters in Niagara Creek suggests that the permafrost is thin. GPR surveys in Mauze Gulch near the spring site indicate that the permafrost has been penetrated and is as thin as 2 m near the spring.

There were no holes drilled in the Melsing Creek/Clyde's Gulch basin but it is fortunate that a large thermokarst study was conducted a couple of km from the mouth of Melsing Creek. A total of 5 holes were drilled in the tundra south of Melsing Creek, ranging from 3-5.5 km south of Melsing Creek, to a depth of 10 m. At this depth the permafrost was not penetrated. This drill data was used in conjunction with GPR and Direct Current Resistivity Surveys to estimate the thickness varied between 20 and 60 m (Yoshikowa and Hinzman 2000). The presence of many springs in Melsing Creek indicate that permafrost is discontinuous in this basin. Again, no survey has been done to accurately define the extent of permafrost but based on field observations, there is approximately 50% permafrost coverage in Melsing Creek. The village of Council lies at the mouth of Melsing Creek. Domestic wells do not encounter permafrost at the mouth of Melsing Creek. Clyde's Gulch is a heavily treed site that lies near the mouth of Melsing Creek. Field observations and supporting well data indicate that the majority of Clyde's Gulch is absent of permafrost. The exception may be at high elevations, above treeline and above the spring that feeds the drainage.

Geology

The bedrock geology in the northern region is mainly metamorphic schist with outcrops of marble being common. The lowlands are typified by unconsolidated sediment generally 10-20 ft thick. The southern part of the peninsula is underlain by bedrock consisting of metamorphic and granitic rocks. Much of the lowlands in the southern part are underlain by 100 ft or more of glacial outwash (Hopkins, 1955).

Soil descriptions were done in both study areas by Michaelson and Ping (2002). The soils in the Council area were described for six different sites. Based on the samples collected in this area almost all samples contained loamy material with mixed mineralogy. Loamy soils ranged from fine to coarse. In higher elevations, the parent material consists of limestone and in these areas soil is present between surface rock outcroppings and cobbles. Other parent material encountered was micaecous schist and colluvium. Eight samples were analyzed near the Kougarok watersheds. Based on these samples, most sites contained parent material of micaecous schist, the exception was one site, which had parent material of alluvial origin. At higher elevations, soils exist between bedrock cobbles. At other sites, fine-coarse loamy soils and silt were encountered.

The active layer thickness in Kougarok and Council is variable within each watershed. It has been measured on many occasions using a thaw depth probe. In general, the active layer is thicker in Council than Kougarok. The average thickness is around 56 cm in Kougarok and 63 cm in Council. In general, basins with continuous permafrost and a shallow active layer will have higher surface soil moisture values than a discontinuous permafrost basin with a larger active layer thickness.

Melsing Creek

Melsing Creek (Figure 3) is the largest stream in the study with a basin area of 80.6 km^2. This is a second order stream as defined by the USGS topographic 1:63,360 map. Melsing Creek flows into the Niukluk River. Development in the Melsing drainage is minimal. There are a few cabins along the creek, some trails, and a historic railroad line on the north side of the watershed. The development in the area was considered to be insignificant and would not impact the hydrologic analysis.

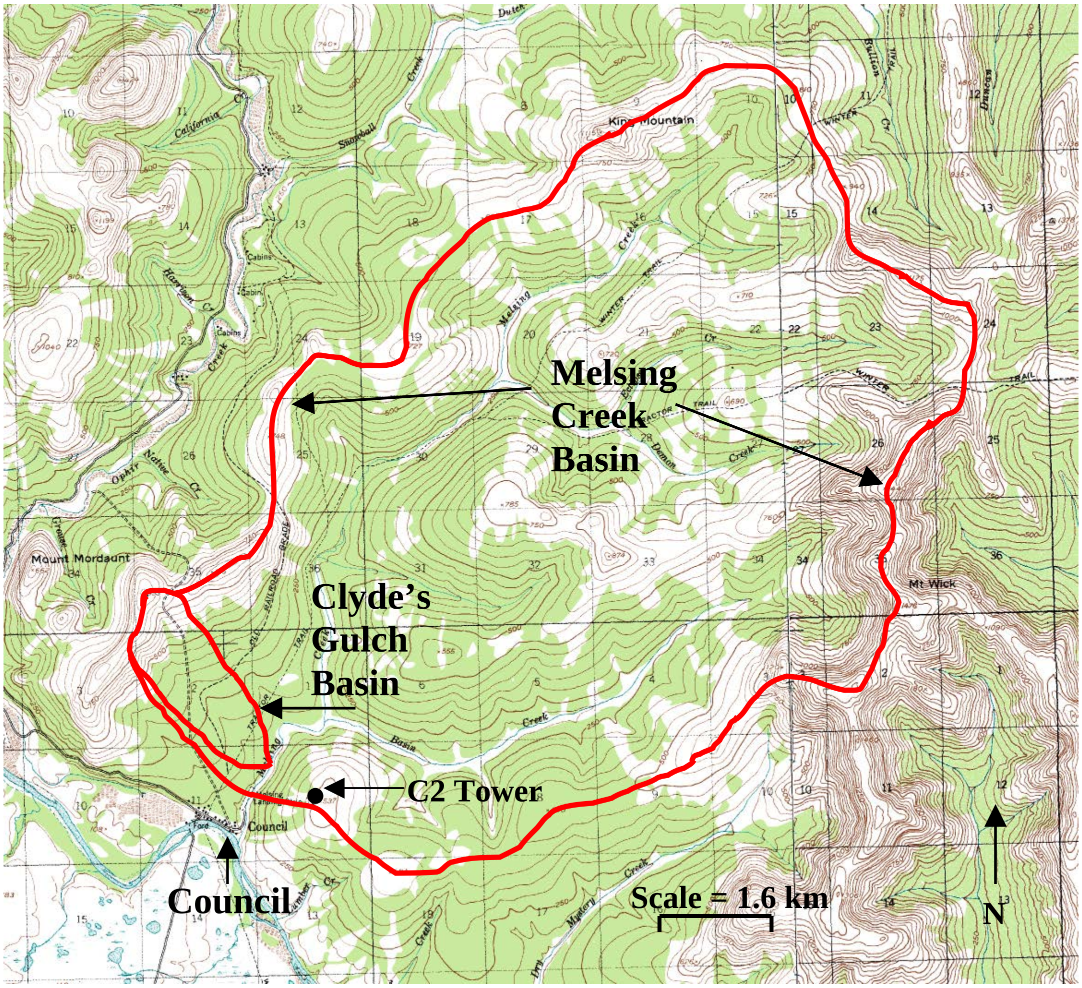

Figure 3. Melsing Creek and Clyde's Gulch study basins.

All streams including Melsing are considered to be typical nival regime basins. The Melsing basin is covered by a large variety of vegetation. The Council area is representative of a subarctic transitional region. It is characterized by boreal forests, white spruce and shrubs at the lower elevations and tundra regions at higher elevations, all located on warm discontinuous permafrost. This region provides a climatic transition to the tussock tundra in the watersheds near Kougarok.

Melsing Creek was chosen as part of this study because of its location and morphology. Melsing Creek is characterized as a discontinuous permafrost basin. Evidence of deep groundwater flow contributing to the water balance can be seen by the many springs in the watershed. The headwaters of Clyde's Gulch contain one spring and another stream that has been sampled is located in Basin Creek, another tributary to Melsing. Other springs do exist and the extensive aufeis formed during the winter of 2000 is partial evidence of this. One type of aufeis formation occurs when flow from the creek freezes and forms ice layers, as the layers get thicker, the water flowing underneath is under pressure, this forces the stream to break through weak points in the ice cover and overflow onto the surface and freeze (Carey, 1973).

The evidence of permafrost melting is clear near the Melsing Creek drainage. There are several thermokarst ponds that are currently being studied south of Melsing Creek, between 3 and 5.5 km from the mouth of Melsing Creek.

A gold dredge located in Melsing Creek, about 4 km from the mouth of Melsing Creek, is evidence of the mining in the area, although the creek itself does not visually appear to have extensive disturbance.

Melsing Creek meets the Niukluk River at an elevation near 23 m. The headwaters rise to an elevation of 450 m.

Clyde's Gulch

Clyde's Gulch is a small spring fed creek that is a tributary of Melsing Creek. It has the smallest drainage area of the study basins at 2 km^2. The catchment has an elevation range from 30 m to 267 m. The spring that feeds the creek and provides the baseflow is located at an elevation between 60 and 76m. The area above this contributes little flow.

Clyde's Gulch is covered in a range of vegetation from tundra at the high reaches of the watershed to white spruce forest where the spring feeds the watershed. At the point where the creek enters Melsing Creek, the vegetation is predominately shrubs. Clyde's Gulch is not defined on the USGS 1:63,360 map as a first order stream but can be located by the incised landscape on the map (Figure 3).

Mauze Gulch

Mauze Gulch has an area of 4.9 km^2 (Figure 4). Permafrost has not been mapped in this area but field observations and drilling samples conclude that the stream is continuously underlain by thin permafrost. It is speculated that there may be areas of discontinuous permafrost under the stream itself based on evidence suggested by Hopkins (1955). The area in and around these watersheds consists mostly of tussock tundra and shrubs.

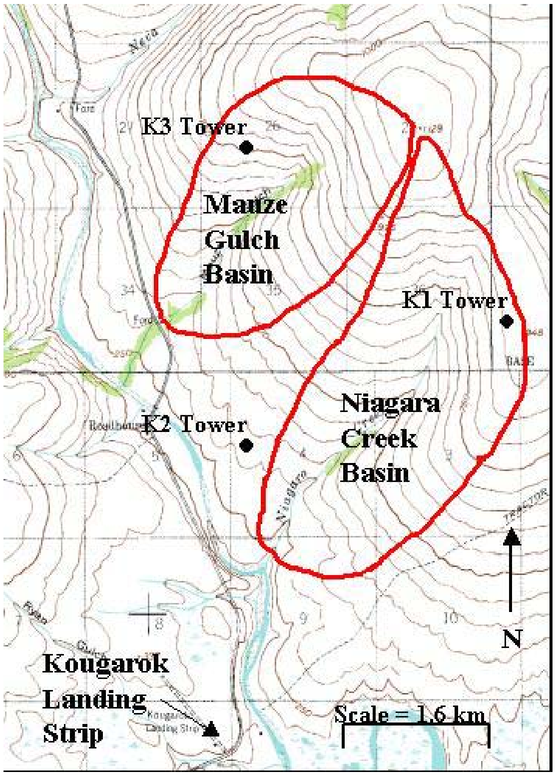

Figure 4. Mauze Gulch and Niagara Creek study areas.

There are no tributaries contributing flow to Mauze Gulch. It is shown as a first order stream on the USGS topographic map although it does not flow year round. Mauze Gulch is covered mainly by tussock tundra (approximately 70%) with smaller areas of birch and willow shrubs (30%) located mostly near the creek. Estimates of vegetation were done using an aerial map and verified by field observation. Mauze Gulch flows into the Kougarok River at an elevation of 120 m and the basin rises to an elevation of 344 m. The stream flows southwest and runs parallel to Niagara Creek.

Niagara Creek

Niagara Creek (Figure 4) flows into the Kougarok River at and elevation of 76 m and the highest point in the catchment is also at 344 m It also flows southwest. The vegetation is very similar to Mauze Gulch though the percentage of tussock tundra is estimated at 80% and shrubs at 20%. The main difference between the two watersheds is that a portion, over 50%, of Niagara Creek was burned in a large tundra fire from July 22 to August 25, 1997.

DATA COLLECTION

An extraordinary data set has been collected as the result of the ATLAS study. Six meteorological towers were installed as part of the two study areas and four stream gaging stations were installed. Snow surveys were conducted on a basin-wide scale each spring. The important aspect of this study is that comparable data sets have been collected for over four years in the study areas.

The data can be broken down into four main categories; snow, soil, meteorological, and stream discharge.

Snow

Each spring, basin-wide snow surveys were conducted before springmelt began. This typically took place in April. The exception to this is in 2002. Field crews were not able to visit the sites before melt began and the snow pack had already ablated to about 50%. In 2002, the calibrated HBV-96 model was used to back calculate the initial snowpack (SWE) because that data was not available. The snow surveys were an attempt to give a reasonable estimate of the overall snow pack for the basins. In 1999, a separate trip was made to Kougarok in April to estimate the snow pack. There was no data collection in Council during the spring of 1999. In 2000, field crews arrived at both field sites before melt initiated and surveys were conducted upon arrival. In 2001, basin surveys were conducted in April, prior to melt initiation.

In Kougarok, spring melt has been monitored since the spring of 1999, and monitoring in Council began in spring 2000. Basin wide surveys each spring of snow depth and density provided the data used to estimate the water equivalent for the basin. In general measurements were made using double sampling techniques outlined in Rovansek et al. (1993). At each site, ten snow samples were taken using an Adirondack snow sampler to get an average density and 50 snow depths were averaged to calculate an average SWE for that site.

In Melsing Creek/Clyde's Gulch, the basin wide snow survey sites were selected to provide sampling sites representative of the entire basin so that the SWEs were averaged from all sites equally to create an average water equivalent for the basin. This is different than how the basin surveys were conducted in Kougarok. In Kougarok, several sites were surveyed and the data was used along with the knowledge of vegetation coverage. An average value was found for shrub sites and one for tundra sites and then the values were weighted depending on percentage of vegetation for each watershed.

In addition to gathering information about the initial snowpack, measurements of ablation were monitored throughout melt. Daily measurements were made at ablation sites in each basin. The sites were chosen to represent the snowpack in different vegetation types. In Mauze Gulch and Niagara Creek a shrub site and a tussock site were chosen. In Melsing, shrub, tundra and forest were represented.

Soil

Soil temperature thermistors were installed at all the meteorological towers in the study through the soil profile. Data were collected every three hours and recorded on Campbell Scientific CR10X data loggers. Temperatures reported are average daily values. Thermistors were installed at incremental depths from 0 cm to 120 cm. The data located near the meteorological tower on Blueberry Hill, C2, near Council show that thawing occurs to a depth of 110 cm for a brief time (Figure 5). Freezing occurs throughout the soil profile.

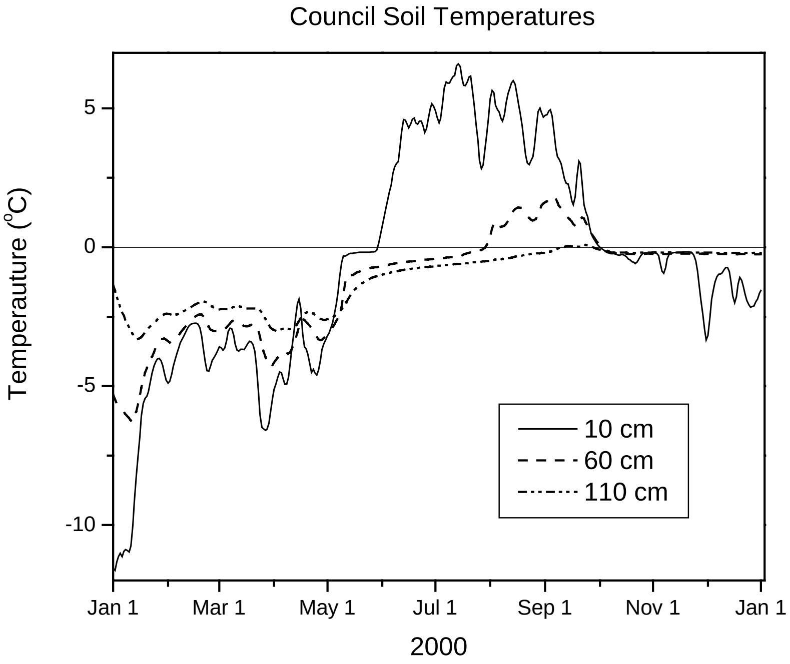

Figure 5. Soil Temperatures at C2 Meteorological Tower near Council.

The soil temperature profile from the K2 tower, near Kougarok, shows that permafrost exists at this site (Figure 6). The soil near the K2 tower is permanently frozen below a depth of 50 cm. The active layer freezes completely throughout the soil profile seasonally.

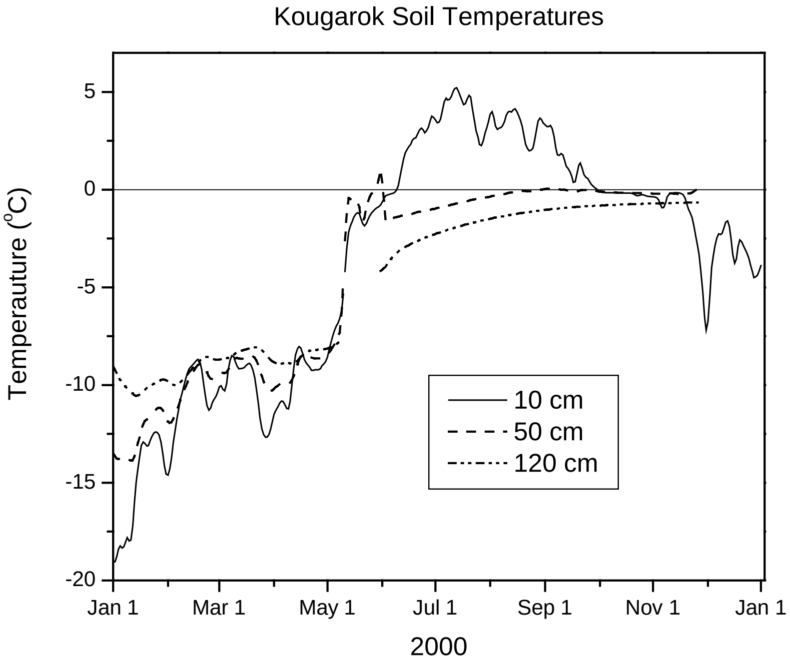

Figure 6. Soil Temperatures at K2 Meteorological Tower near Kougarok.

Meteorological Data

Meteorological towers were installed in six locations, three in Council and three in Kougarok. In Kougarok, a 10-meter tower was installed on a plain separating Mauze Gulch and Niagara Creek. This tower was named K2 (Figure 4) and measured air temperature, relative humidity, wind speed, wind direction, rainfall, soil moisture profiles, soil temperature profiles, incoming and outgoing long-wave radiation, incoming and outgoing short-wave radiation and net radiation. Two 3-meter towers were also installed in the basins. K1 is located on a ridge at the head of Niagara Creek. K3 is located in the Mauze Gulch basin on the north side of the watershed (Figure 4). K1 and K3 are instrumented with air temperature, relative humidity, wind speed, wind direction, rainfall, soil moisture profiles, soil temperature profiles, and net radiation.

In Council, a 10-meter tower was installed near the top of the Blueberry Hill (Figure 3) near the outlet of the Melsing Creek basin. This tower is named C2 and it is on a south-facing slope. It is instrumented with air temperature, relative humidity, wind speed, wind direction, rainfall, soil moisture profiles, soil temperature profiles, incoming and outgoing long-wave radiation, incoming and outgoing short-wave radiation and net radiation. Two smaller towers are located outside of the study basin. C1, located on the flats about 5 km south-southwest of Council. This tower was used when data was not available from the C2 tower. C1 is instrumented with air temperature, relative humidity, wind speed, wind direction, rainfall, soil moisture profiles, soil temperature profiles, and net radiation. C3 is another 3 meter tower located in the Guy Rowe watershed approximately 18 km southwest of Council and was not used for this research but is part of the ATLAS study.

Stream Data

The discharge was monitored several times a day during snowmelt by taking individual measurements using a Flowmate current meter and a wading rod. On several occasions, flow in Melsing Creek was estimated when the creek could not be waded or crossed in a boat due to massive ice rafts. In these cases estimates if the flow were made to the best of the observers capabilities using estimated measurements of stream width, main channel velocity and estimated average depth. When the channel could safely be waded, measurements of depth, velocity and width were collected over an interval to calculate a total discharge for the stream, according to guidelines established by the Buchanan and Somers (1969). In all streams, other than Melsing Creek, it was possible to obtain actual measurements from wading the creek.

In the Council creeks, measurements were made before snowmelt initiation to obtain values for baseflow. In Kougarok, the creeks were measured as soon as water started to flow in the channel. An attempt was made to measure the diurnal variations throughout melt. In all cases, when a stable channel was established and all ice was gone from the channel, pressure transducers were installed to provide a continuous record of discharge. Data was recorded using Campbell Scientific CR10X recorders on an hourly interval.

METHODS

Hydrograph Simulation

This study was conducted over a period of four years, 1999-2002. The study began in Kougarok (Mauze Gulch and Niagara Creek) in the spring of 1999 with the monitoring of spring melt; maximum snow accumulation and ablation and stream discharge. Stream discharge was measured as soon as the streams began to flow, usually 2-3 times/day in order to monitor diurnal variations. Continuous recorders (Campbell Scientific CR10X recorders), pressure transducers and Stevens water level recorders, were installed in these watersheds once the snow had melted from the channel and the channel was considered stable and a stage/discharge relationship could be created. These instruments recorded the voltage hourly on a data logger, which was then converted to a depth. River discharge, during the summer, was calculated using a stage/discharge relationship. Site visits were made periodically during the summer to gage the streams to provide more data for the stage/discharge relationships.

Melsing Creek was added to the data network during the summer of 1999 when the creek was also instrumented with pressure transducers and a Stevens water level recorder. From the spring of 2000 through the fall of 2002, all four watersheds were monitored and continuous discharge stations were maintained throughout the duration of the three years. Hydrographs showing the manual measurements and the calculated discharge, using data from the pressure transducer and a stage/discharge relationship, for all basins in this study can be found in Appendix A.

There are large variations in the quantity of measurements taken to create the stage/discharge relationships. This makes it necessary to provide a discussion on the methods of data collection and the frequency that data was collected. The main obstacle that needed to be overcome in this study was the logistics. Fieldwork in remote regions always creates problems when it comes to collecting complete data sets. When creating stage/discharge relationships it is imperative that manual measurements of discharge are collected for a variety of river stages from very low flows to very high flows. With only a few trips scheduled each year, this makes it difficult to gage a full range of discharge rates.

In Melsing Creek and Clyde's Gulch it was fortunate that measurements were taken once or twice daily throughout the summer of 2000, establishing a very complete relationship. In the other watersheds, Niagara and Mauze, there were years that only a handful of measurements were made and these hydrographs are regarded as a best estimate.

The computer graphing program, Origin, was used to calculate the equations used to create the stage/discharge relationships. Some pressure transducers had valuable temperature data and temperature corrections could be made to the continuous data to account for daily temperature fluctuations. In cases where temperature data could be used, a program was added to Excel called Essential Regression. This program related the temperature data and pressure transducer voltage to river stage by creating a double regression relating voltage and temperature to river stage. Two equations need to be made to create the hydrographs. The first relates the stage to the pressure transducer voltage (and temperature when available). The second relates the stage to the discharge.

Melsing Creek, Mauze Gulch and Niagara Creek Stevens water level recorders were installed as back-up source of water-stage data. This was helpful in Melsing Creek in 1999 because the Stevens recorders are not affected by temperature fluctuations and the pressure transducers showed a large affect due to the temperature.

There are a few instances where there are gaps in the continuous record in Niagara Creek due to pressure transducer malfunction. In the cases where this occurred, a relationship was created between Mauze Gulch and Niagara Creek. This relationship was derived from plotting the flows for the rest of the year and establishing a relationship between the two streams. The relationship was then used to estimate the flow from Mauze Gulch to what Niagara Creek would closely be and the gaps were filled in using this estimated data.

Ablation

Ablation data were collected at several sites in both Kougarok and Council areas. In the Kougarok area, ablation was measured typically at four sites. The sites were chosen to represent the different vegetation types of the area (shrub and tussock). In the Council area ablation was also measured at several sites to monitor the variability of the snowmelt in different vegetation types. In Council 3-4 sites were measured during the spring (tree, short shrub, tall shrub, and tundra).

Ablation was measured the same way the snow surveys were conducted using double sampling according to Rovansek et al (1993). An Adirondack snow sampling tube was used to get 10 measurements of depth and weight, these data were converted to a snow density. In addition, usually 50 measurements of depth were taken in the immediate area and an average SWE was created for the site. In most years, monitoring of ablation was initiated before the snow pack started to ablate and continued until all the snow had melted. In 2002, the snow pack had already begun to ablate before measurements were started.

The ablation curves derived in this study came from field data that was collected as described above. The various measurements were area weighted based the proportion of vegetation in the basin. In Mauze Gulch, a shrub site and a tussock site were measured daily throughout spring melt; these data were then weighted based on the proportions of tussock/shrub (0.7/0.3). In Niagara the same collection method was used but weighted at 0.8/0.2. Four sites were measured in Council (tundra, high shrub, low shrub, and forest). The following proportions were used to weight the data and obtain one curve 0.1/0.45/0.45, where high and low shrub sites were averaged and then weighted as 0.45.

Recession Analysis

The recession constants were found using a common method outlined in McNamara et al. (1997). This is a common method used in many hydrology texts. Equation 1 approximates the falling limb of the hydrograph. The measured hydrograph is plotted on semi-log scale, a break in the slope of the hydrograph can be seen for different components of the hydrograph. The lower part of the recession curve is believed to represent baseflow. A trend line is drawn through the baseflow recession on the hydrograph and the following equation was used to calculate the recession constants.

Equation 1: $Q=Q_o e^{(-t/t^*)}$

Where Q is the discharge in cms at time t hrs. after the recession started. Q_o is the discharge at the beginning of the recession in cms, and t* is the recession constant.

As Dingman (2002) points out, there are several methods that can be used for baseflow separation. He also states that if a consistent method is used, base-flow separation can be a useful tool for comparing streamflow in different watersheds. In this study a consistent routine was used to evaluate the hydrographs. If rain events made it difficult to discern the recession of the baseflow, then that event was not analyzed. The goal was to get an average recession constant for each watershed in order to compare the watersheds.

Water Balance

A water balance was done for each watershed, each year. A water balance equation that has been applied to arctic watersheds (Woo, 1983) is:

Equation 2: $\Delta S = P - E - Q$

Where; ΔS=change in basin storage, P=precipitation, E=evapotranspiration, Q=runoff

Cumulative precipitation values were obtained from the meteorological stations located in each basin. Snow pack values were obtained from surveys done in the spring with the exception of 2002. Values from 2002 were obtained from the HBV model. Runoff values were obtained by finding the cumulative runoff in each stream from the hydrograph.

This thesis used values of total precipitation (rain and snow) and runoff to calculate ratios of runoff/precipitation in water balance calculations. Ratios of runoff/precipitation were calculated for both the spring melt season and the summer season. These ratios give insight into the relative amount of water that enters the subsurface at certain times of the year. The difference in the ratios suggest difference in the amount of permafrost in a watershed and give insight into the character of a basin.

HBV-96

The original HBV model was developed by 1975. It was developed in Sweden by the Swedish Meteorological and Hydrological Institute (SMHI) as a conceptual runoff model. The original intent was to have a model that would work well in Scandinavian countries and could be used for operational forecasting. Over the many years it has been in use, it has been shown that it works well in many locations around the world. It has been applied in over 30 countries (Lindström et al., 1997). In the early 1990's the model was revised to incorporate spatial representation of data. The revision produced the HBV-96 version that was used in this study.

It is important to remember that the parameters in the HBV model are calibrated to the basin but they may not be physically representative even though they are based on physical processes. When setting up the model, a concerted effort was made to keep the model parameters representative of the true physical system. In some cases this is not possible based on the way the model is structured.

The HBV-96 model is a conceptual runoff model. Although it is considered to be a simple model by many standards, it performs well in the Arctic because the parameters that control runoff in the model are also the parameters that govern the natural system. The important processes in these watersheds are snowmelt, soil moisture, and surface runoff.

There are three main components to the structure of the model (Bergström, 1976).

1) Snow accumulation and ablation, which is based on a degree-day approach.
2) Soil Moisture, based on potential evaporation
3) A response function

The model is designed run on a daily time steps. Although, it has been shown that it handles data taken every two hours with precision (Hinzman and Kane, 1991). The input into the model consists of daily values of temperature and precipitation, monthly values of potential evaporation, and estimates of the initial SWE.

There are several subroutines incorporated in the model. They include snow accumulation and melt, soil moisture, runoff generation and runoff routing.

The snowmelt routine is based on a degree-day relationship.

Equation 3: $M = C_o (T-T_o)$

Where: M = snowmelt (mm/day), C_o= degree-day factor (mm/°C*day), T = Surface air temperature (°C), and T_o= Threshold temperature (°C).

The snowpack is modeled to retain water until a certain amount of the snowpack has been melted. This is termed the 'water holding capacity'. This parameter is a function of the properties of the snowpack. In the field, snow densities were recorded and monitored during spring melt, but no attempt was made to correlate the field surveys to the water holding capacity values used in the model. In general, the water holding capacity of the snowpack decreases as melt occurs (Bergström, 1976). During melt an acceptable value relating to real systems is between 2 and 15%; the value of freshly fallen snow can be as high as 55%; ten percent is a typical average value used in many models (Bergström, 1976).

The runoff is mainly controlled by the soil routine. There are three main parameters in the model that control this routine. One is the limit for potential evapotranspiration. The modeler defines a limit of soil moisture above which the evapotranspiration reaches its potential value. Field capacity is the soil moisture value, which, if exceeded water can drain from the soil thus contributing to runoff. The last main parameter is called Beta, which defines how much water goes to soil moisture from each increment of snow or rain.

Permafrost was not a consideration when developing the HBV model. Bergström (1976) concluded that frozen ground was probably accounted for with the free parameters in the model. Hinzman and Kane, (1991) found that the HBV model adequately accounted for permafrost by setting the percolation parameter = 0, effectively prohibiting water from entering the groundwater layer in the model. In a study by Sand and Kane (1986) the HBV model showed a poor ability to simulate both snowmelt runoff and rainfall runoff. The HBV model consistently underestimated snowmelt and overestimated rainfall. It was discovered that the model performed much better if seasonally frozen ground was accounted for by calibrating two sets of parameters, one set for spring melt when the ground is frozen and one set for summer when the active layer is thawed. One set of parameters was used for both spring melt and summer in this thesis because the model did not show the same pattern of overestimation and underestimation of runoff. In this thesis, no discernable pattern could be found to apply two sets of parameters. In this study the percolation was set = 0 in the basins that are continuous in permafrost and in the basins that are discontinuous, water was allowed to percolate to the lower soil moisture zones.

Bergström warns against using the parameters from the upper response box to describe the model basin. This is because it is hard to relate the slow and quick runoff components to actual physical processes. It is well documented that the lower response box does correlate well to the ground-water contribution (Bergström, 1976). This provides confidence in the model structure used in this study to simulate the occurrence of permafrost.

It is possible to run the model for several basins that contribute to one basin and to divide the basin into several elevation and vegetation zones (SMHI, 1996). The basins in this study were small enough that there was no linking of subbasins or embedding elevation zones. When running the model, the parameters designed to correct for rainfall and snowfall were not used. An elevation correction was not used either. The elevation range in these watersheds was not great enough to markedly change precipitation measurements. It is important to note that conceptual models such as the HBV-96 use average parameters over a large area. Although there are correction factors for rainfall and temperature, they were not used in this study. There is a tendency for rain gages to under-catch the amount of precipitation (Benson, 1982) but it was found that the model performed adequately without applying correction factors.

Calibration of the model mostly consists of visually inspecting the simulated hydrograph and observed hydrograph and adjusting empirical values to achieve a sum of squares value that is acceptable.

Each watershed was analyzed with HBV-96 for each year that complete data sets were available. See Table 1 for parameters used to calibrate the HBV model. Initially, each watershed was run with identical parameter sets and then adjusted to get an optimum fit. Input consisted of temperature, precipitation, runoff, and initial snow-pack. The hydrographs were examined and the calibration process was iterative. Each watershed was worked with individually. When possible, one unique parameter set was used for each watershed. In some cases reasonable results could not be achieved with identical parameter sets for each year. In these cases only one parameter was changed between years. This only occurred in Niagara Creek and Clyde's Gulch.

Table 1. HBV-96 parameters used in the calibrating the model.

cfmax= snow melting factor (mm/degree day)
tt= threshold temperature (ºC)
whc= water holding capacity
cfr= refreezing factor
fc= field capacity (mm)
lp= limit of evaporation
beta= exponent for drainage from soil
K4= recession coeff for lower response box
perc= percolation to groundwater (mm/day)
K0= top coeff for upper response box
K1= second coeff for upper response box
K2= third coeff for upper reposnse box
uzl0= lower limit for KO (mm)

There are three different soil moisture accounting routines that can be used in the version of HBV used. The routine that was chosen incorporates a parameter called ‘perc’ which in theory represents the percolation of water from the upper soil moisture zone to the lower zone, or ground-water zone. This was chosen because we wanted the model to reflect the physical conditions of the watershed, two watersheds having no ground-water contribution and two watersheds with ground-water contributions. The model was set up combining knowledge of the physical system with the model structure. In as much as possible, physical reality was represented in the model. For instance in Melsing Creek and Clyde’s Gulch where there is discontinuous permafrost, we used the parameter percolation to simulate recharge to groundwater. In Mauze Gulch and Niagara, the percolation was set = 0 on the basis that there is no recharge occurring.

The HBV-96 model was run on daily time steps in all watersheds for all years included in this hydrological analysis, a total of 14 model runs. It was also run on hourly time steps in

Mauze Gulch and Melsing Creek during the 2000 season. This was done to evaluate the sensitivity of the model to finer time steps. Modeling the snow ablation was hoped to be improved by using hourly time increments.

RESULTS/DISCUSSION

Hydrograph Analysis

Hydrographs were analyzed and compared between watersheds. The specific discharge is the discharge of the basin normalized by dividing by the basin area so that basins of different size can be compared. Melsing Creek consistently had the highest specific discharge and Niagara usually the lowest with Clyde's Gulch being the second highest and Mauze third (Figures 7-14). The specific discharge is higher during low flows in the basins with less permafrost because the baseflow is the contributing factor. It can be seen, in most cases, that the specific discharge in Melsing Creek and Clyde's Gulch is greater than Niagara Creek and Mauze Gulch at almost all stages of flow.

Rainfall between the two regions, Council and Kougarok, varies. Therefore, the hydrographs between the two regions reflect the different contributions from storm events. The important component of the hydrographs to focus on is the baseflow. The baseflow component is seen as a direct measure of the groundwater contribution and therefore, an indication of discontinuous nature of permafrost in the watersheds that contain baseflow. The absence of baseflow in Mauze Gulch and Niagara Creek is observed during the summer of 2002 when both creeks ceased flow in mid-July.

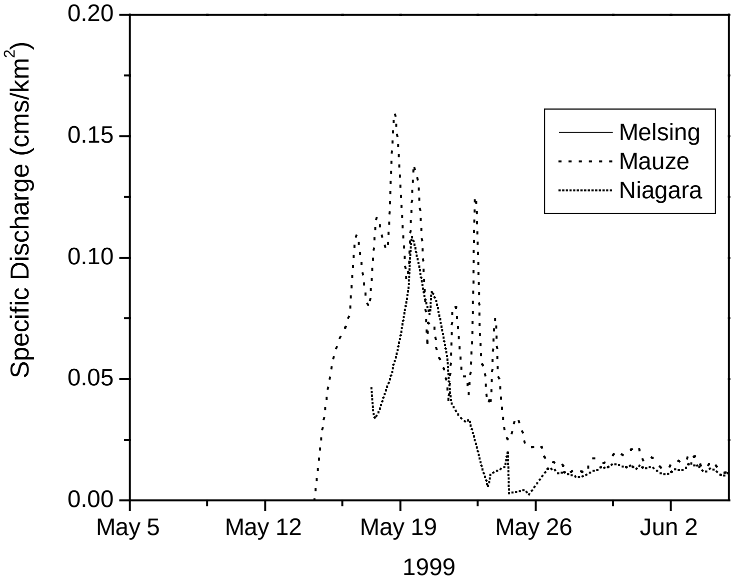

Figure 7. Specific discharge for the spring snowmelt 1999.

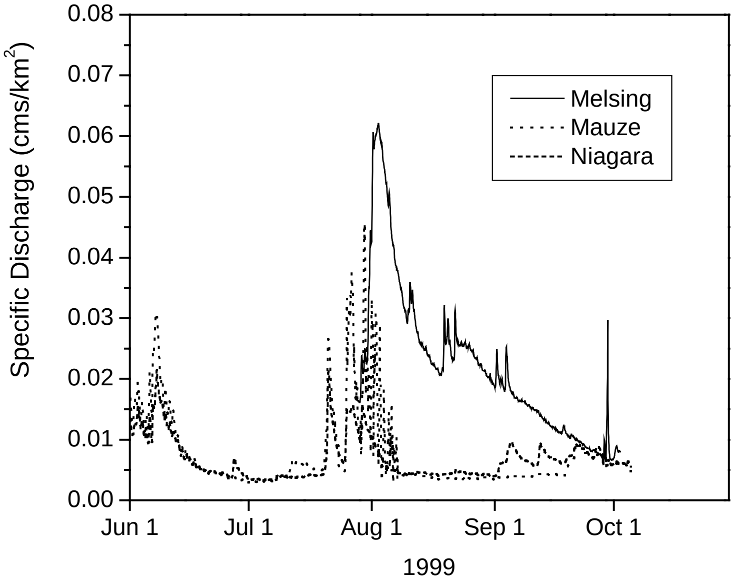

Figure 8. Specific discharge for the summer of 1999.

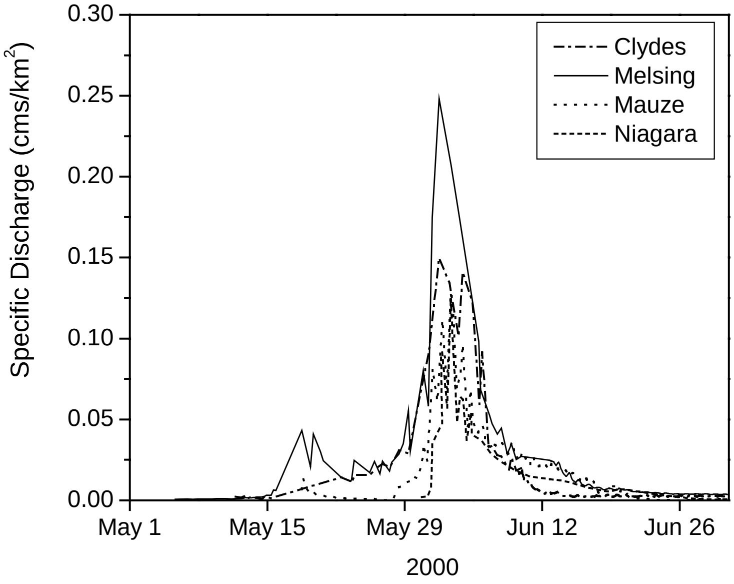

Figure 9. Specific discharge for spring snowmelt 2000.

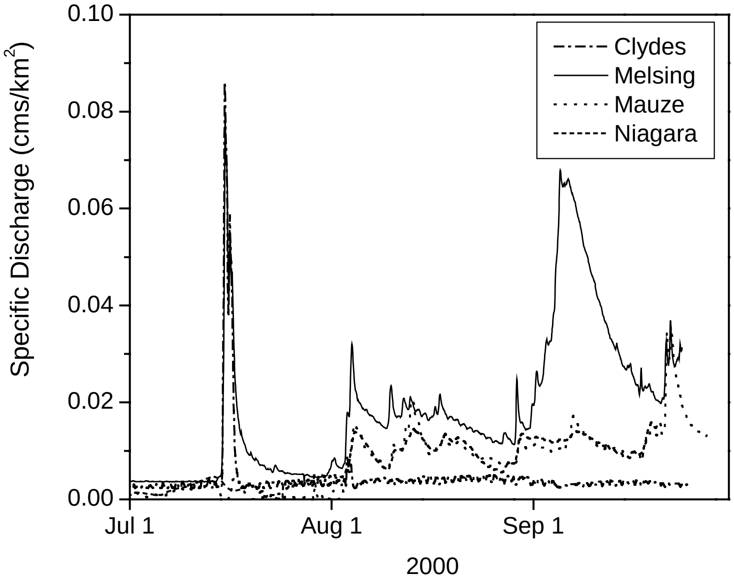

Figure 10. Specific discharge for summer 2000.

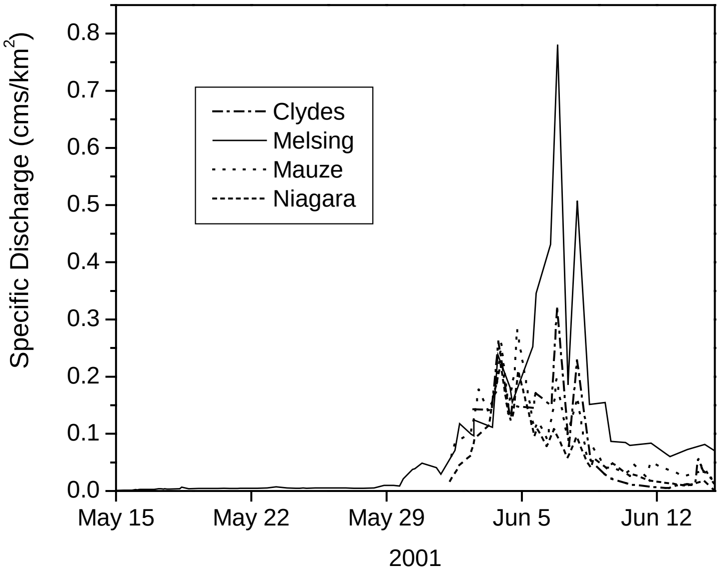

Figure 11. Specific discharge for the spring snowmelt 2001.

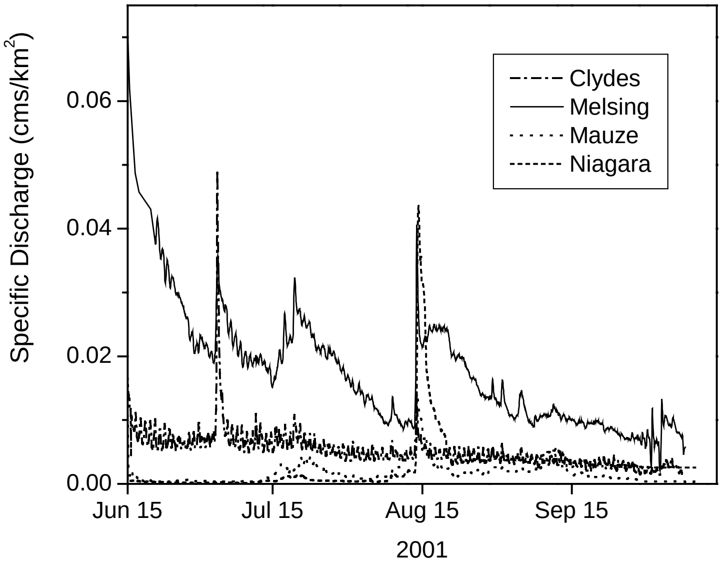

Figure 12. Specific discharge for summer 2001.

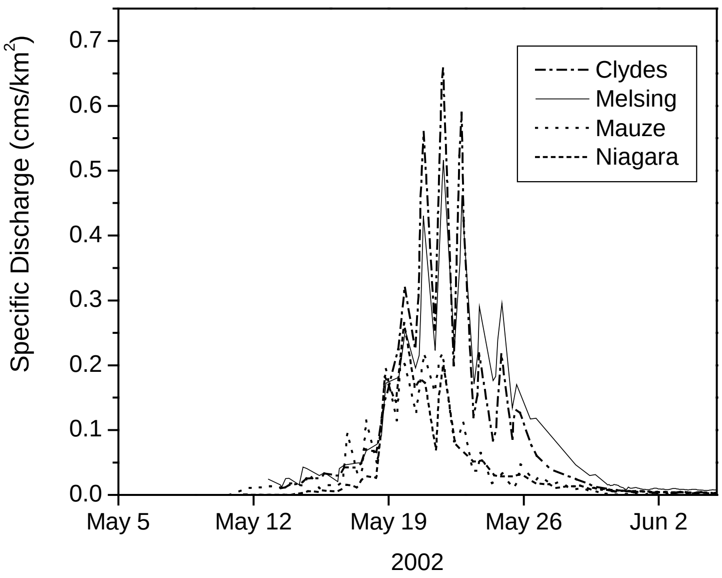

Figure 13. Specific discharge for spring snowmelt 2002.

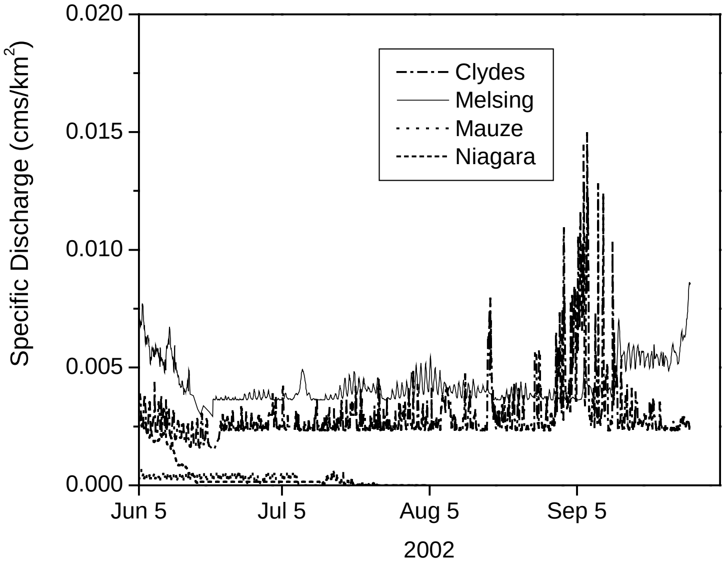

Figure 14. Specific discharge for summer 2002.

Field observations validate the original hypothesis that Mauze Gulch and Niagara Creek do not have significant baseflow. In winter there is minimal aufeis formation, limited to the headwaters, to suggest groundwater flow. The presence of aufeis does suggest that there is a small amount of sub-permafrost seepage near the headwaters of the basins in Kougarok. During the summer of 2002, there was very little precipitation throughout the Seward Peninsula and both streams in Kougarok went dry, another indicator that there is no baseflow. Graphing the specific discharge verifies these observations. Analysis of the hydrographs and the specific discharge illustrate that Melsing Creek and Clyde's Gulch have a baseflow (groundwater) component. The evidence for year-round baseflow is most obvious in the late winter when aufeis formations sometimes completely fill the river channel over 1 m thick in Melsing Creek. Field observations show that Clyde's Gulch has a spring that flows all winter. Temperature measurements (2ºC) of the water flowing from the spring indicate that the spring is not flowing through permafrost.

It has been well documented, and stated previously, that spring runoff, as a result of snowmelt, is usually the most important annual hydrologic event in large arctic watersheds. In small watersheds snowmelt runoff usually produces the largest runoff of the season, but the largest floods on record are always due to rainfall or a combination of snowmelt and rainfall. This is because the rate of rainfall is greater than the rate at which snow can melt. It has been determined that, in some watersheds, over three quarters of the annual discharge is from snowmelt (Woo, 1983; Kane et al., 1990). During the duration of this study there were no summer rain events that created floods that were greater in volume than the snowmelt floods. This demonstrates that all the streams in this study have a nival regime where snowmelt floods are the dominant event of the year.

Recession analysis is another way to quantify the differences between various basins. It would be expected that in larger watersheds, the recession constant would be smaller, meaning it takes longer for the stream to recede to baseflow, and that continuous permafrost basins will have a longer the recession time. These analyses show both of the above relationships to hold true in the basins studied (Tables 2-5).

Table 2. Summary of recession constants for Clyde's Gulch.

Clyde's Gulch			
	2000	2001	2002
K	0.022	0.017	0.019
hours	46.4	58.1	52.1

Table 3. Summary of recession constants for Melsing Creek.

Melsing Creek			
	2000	2001	2002
K	0.003	0.003	0.004
hours	304.4	364.6	249.5

Table 4. Summary of recession constants for Mauze Gulch.

Mauze Gulch				
	1999	2000	2001	2002
K	0.008	0.008	0.010	0.007
hours	131.4	122.2	101.2	134.2

Table 5. Summary of recession constants for Niagara Creek.

Niagara Creek				
	1999	2000	2001	2002
K	0.005	0.010	0.009	0.008
hours	198.9	102.7	113.5	125.6

Melsing Creek had the longest recession times due to the large area of the basin. Clyde's Gulch had the quickest times as a result of it being a much smaller basin than the others. Clyde's is also significantly less than the other basins due to the presence of permafrost in the other basins. There is no discernable difference between Mauze Gulch and Niagara Creek for each individual year but when the recession time is averaged over the four years, Niagara Creek has an average recession time longer than Mauze Gulch, probably because the Niagara basin is larger. It appears the fire, which occurred in the Niagara Creek basin in 1997, did not affect the stream runoff characteristics.

Snowmelt Analysis

Analysis of the ablation data, in Mauze Gulch and Niagara Creek, (Figures 15 and 16) shows that melt completed earlier in Niagara Creek than Mauze Gulch each year. The SWE in Niagara Creek was less then Mauze Gulch. This is primarily a result of the distribution of vegetation. It would be expected that the amount of snow that falls in the basins in Kougarok is the same but the redistribution of the snow is responsible for the differences seen during spring melt. Mauze Gulch has more shrubs than Niagara Creek, which captures more snow in the vegetation resulting in a higher SWE.

Snowmelt in the Arctic and Subarctic generally occur over a short time period, typically less than 10 days. During the course of this study, the snowpack ablated usually from 7-10 days. In every basin, the 2002 melt concluded the earliest followed by 1999, 2000, and 2001 in that order (Figures 15– 17).

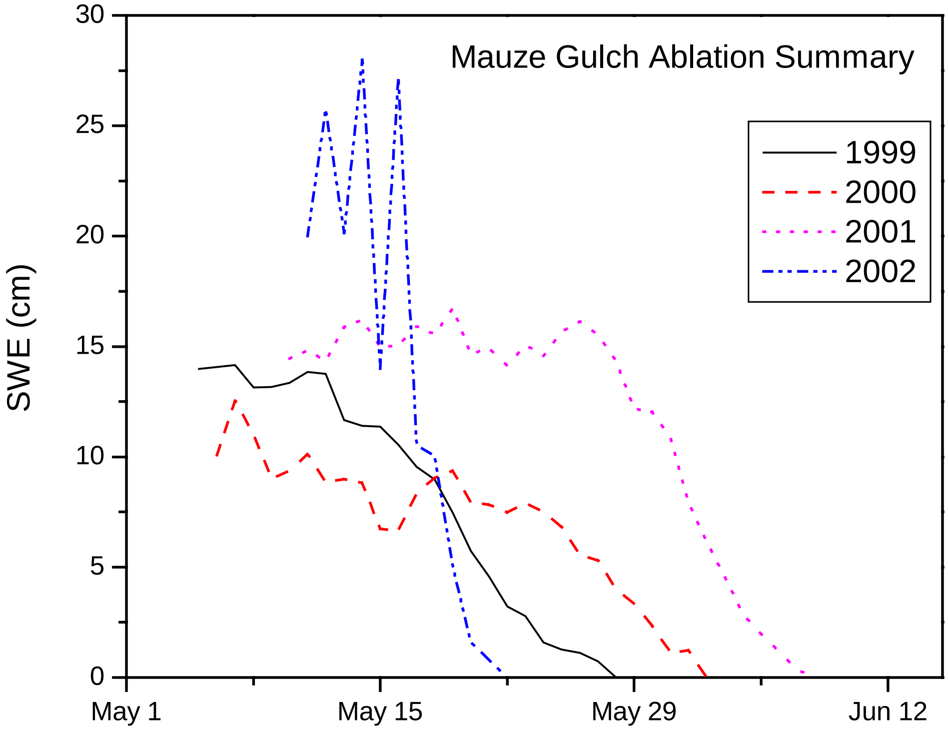

Figure 15. Ablation summary of Mauze Gulch

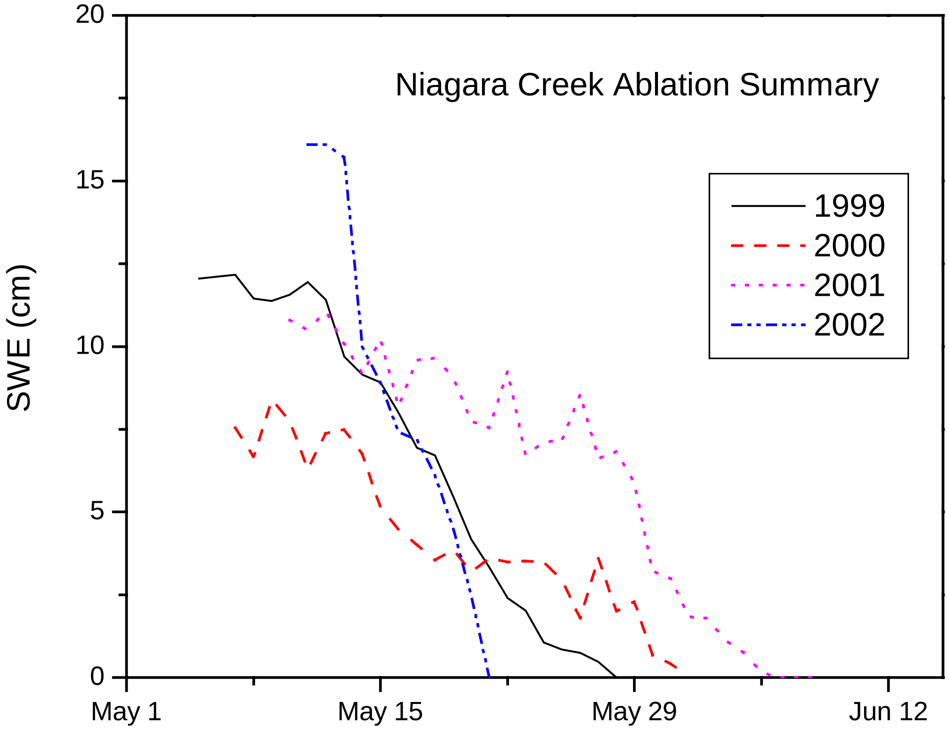

Figure 16. Ablation summary of Niagara Creek

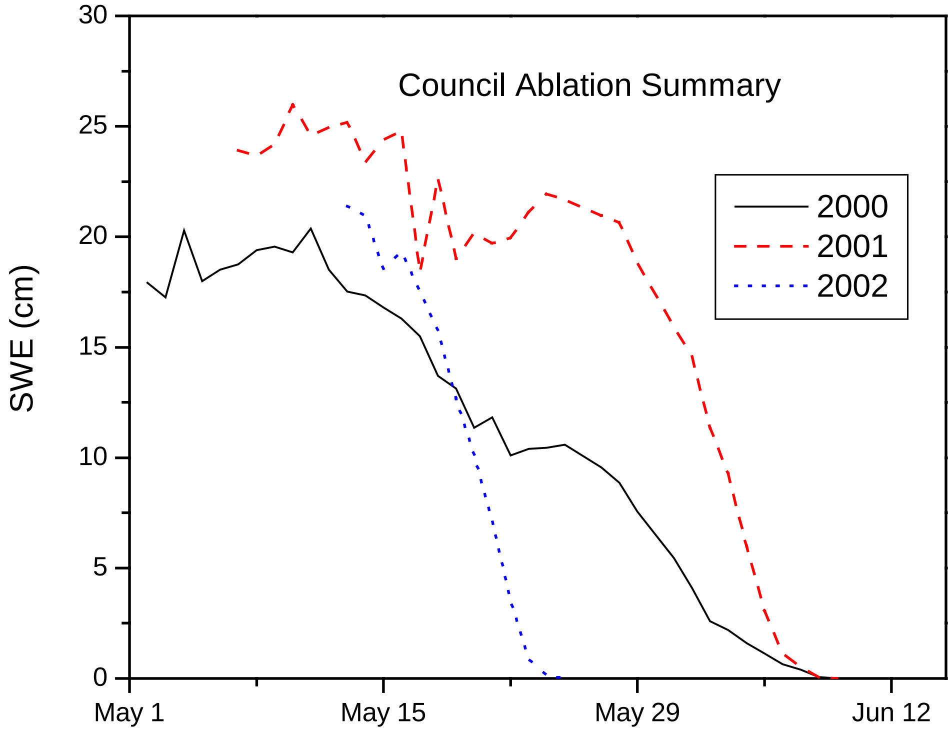

Figure 17. Ablation summary of Council sites.

Water Balance

By studying the water balance computations (Tables 6-9) for each of the watersheds we can see that consistent differences exist between them. A straightforward analysis can be done by comparing the ratios of rainfall/runoff. They were calculated for the snowmelt period and the summer period. These numbers can lend insight into the relative amount of water that enters into the groundwater system. Hydrologists agree that a water balance is an important part of characterizing the hydrology of a basin.

Tables 6 to 9 show the water balance for all the watersheds and years that data were collected. Table 10 is a summary of the hydrology of the watersheds and the average values obtained from analyzing the water balance and the recessions constants. The first relationship that is apparent when studying these data is that the pattern of the ratio of runoff/precipitation changes consistently. For example, in all watersheds the summer of 2000 displayed the lowest ratio and the highest was in 2001.

Table 6. Clyde's Gulch water balance summary for 3 years.

Clyde's Gulch									
Year	Snow Water Eq. (mm)	Summer Precip. (mm)	Total Precip. (mm)	Snow Runoff (mm)	Summer Runoff (mm)	Total Runoff (mm)	$\frac{R_{snow}}{P_{snow}}$	$\frac{R_{rain}}{P_{rain}}$	$\frac{R_{total}}{P_{total}}$
1999	NA	NA	NA	NA	NA	NA	NA	NA	NA
2000	177.5	328.5	506.0	89.3	33.2	122.5	0.50	0.10	0.24
2001	273.1	197.0	470.1	84.5	50.7	135.3	0.31	0.26	0.29
2002	220.0	171.0	391.0	182.5	28.9	211.5	0.83	0.17	0.54
Ave.	223.5	232.2	455.7	118.8	37.6	156.4	0.55	0.18	0.36

Table 7. Melsing Creek water balance summary for 3 years.

Melsing Creek									
Year	Snow Water Eq. (mm)	Summer Precip. (mm)	Total Precip. (mm)	Snow Runoff (mm)	Summer Runoff (mm)	Total Runoff (mm)	$\frac{R_{snow}}{P_{snow}}$	$\frac{R_{rain}}{P_{rain}}$	$\frac{R_{total}}{P_{total}}$
1999	NA	NA	NA	NA	NA	NA	NA	NA	NA
2000	180.8	328.5	509.3	144.7	142.8	287.6	0.80	0.43	0.56
2001	273.1	209.1	482.2	210.4	194.9	405.3	0.77	0.93	0.84
2002	220.0	171.0	391.0	208.0	46.7	255.4	0.95	0.27	0.65
Ave.	224.6	236.2	460.8	187.7	128.1	316.1	0.84	0.55	0.69

Table 8. Mauze Gulch water balance summary for 4 years.

* Values are not reasonable and are not used in averages.

Mauze Gulch									
Year	Snow Water Eq. (mm)	Summer Precip. (mm)	Total Precip. (mm)	Snow Runoff (mm)	Summer Runoff (mm)	Total Runoff (mm)	$\frac{R_{snow}}{P_{snow}}$	$\frac{R_{rain}}{P_{rain}}$	$\frac{R_{total}}{P_{total}}$
1999	197.5	93.8	291.3	96.5	63.9	160.4	0.49	0.68	0.55
2000	109.2	148.0	257.2	67.0	61.3	128.3	0.61	0.41	0.50
2001	100.6	123.0	223.6	105.0	25.3	130.3	1.04*	0.21	0.58
2002	126.0	35.3	161.3	86.9	8.8	95.6	0.69	0.25	0.59
Ave.	133.3	100.0	233.4	88.9	39.8	128.6	0.60	0.39	0.56

Table 9. Niagara Creek water balance summary for 4 years.

* Values are not reasonable and are not used in averages.

Niagara Creek									
Year	Snow Water Eq. (mm)	Summer Precip. (mm)	Total Precip. (mm)	Snow Runoff (mm)	Summer Runoff (mm)	Total Runoff (mm)	$\frac{R_{snow}}{P_{snow}}$	$\frac{R_{rain}}{P_{rain}}$	$\frac{R_{total}}{P_{total}}$
1999	145.1	98.8	243.9	50.9	60.2	111.1	0.35	0.61	0.46
2000	92.1	157.0	249.1	46.3	53.9	100.2	0.50	0.34	0.40
2001	86.3	126.5	212.8	79.3	27.9	107.1	0.92*	0.22	0.50
2002	130.0	35.3	165.3	73.4	10.1	83.5	0.56	0.29	0.51
Ave.	113.4	104.4	217.8	62.5	38.0	100.5	0.47	0.36	0.47

Table 10. Summary of the basic hydrology components of the study watersheds.

	Clyde's	Melsing	Mauze	Niagara
Basin Area (km^2)	2	80.6	4.9	6.5
Baseflow	yes	yes	no	no
Permafrost	0-20%	~50%	100%	100%
Snowmelt R/P	0.55	0.84	0.6	0.47
Summer R/P	0.18	0.55	0.39	0.36
Total Ave. R/P	0.36	0.69	0.56	0.47
1/K (h)	52.2	306.2	122.3	135.2
# years of data	3	3	4	4

Clyde's Gulch had the lowest ratios of r/p. This suggests that more recharge occurred to the aquifer in Clyde's Gulch than in other watersheds. The snowmelt and summer ratios in Melsing Creek show that more runoff/precipitation occurs in this basin than the other basins. Melsing Creek is largely affected by baseflow from the many springs that contribute to runoff. Groundwater discharges into Melsing Creek from the extensive spring network. This dominates the flow in this basin and limits the amount of water that infiltrates into the system. Clyde's Gulch is fed by one small spring that contributes to a small part of the watershed near the outlet of the basin. The majority of Clyde's Gulch is recharged by precipitation that infiltrates vertically into the ground, due to the low occurrence of permafrost and contributions of flow from a spring only at lower elevation.

Table 10 presents the average values for snowmelt and summer r/p; the snowmelt r/p is greater than the summer r/p in each watershed. This suggests that proportionally more water is leaving the basins as runoff during the melt period due to the effects of active layer being frozen, which limits infiltration.

Some values appear questionable when studying the water balance tables. The first occurs during the 2002 season in Clyde's Gulch. The r/p =0.54 which is significantly higher than the previous years which were 0.24 and 0.28 respectively. The snowmelt flood in 2002 was an anomalous event in this basin, one that has not occurred in many years. This is verified by field observations and the fact that the vegetation was stripped from the banks of the stream during this event and the channel was partially re-aligned. More overland flow (compared to other years) may have occurred during this flood event causing a higher r/p ratio.

Another anomalous r/p ratio is found in Melsing Creek during the summer of 2001, where rainfall r/p=0.86. This is in contrast to a rainfall r/p=0.43 and 0.27 in 2000 and 2002. It is not unusual to have large variations from year to year but without further study and additional years of monitoring it is difficult to understand what is normal for this basin.

The r/p ratios are very consistent from year to year in both basins in Kougarok with the exception of the snowmelt ratios in 2001. The unreasonable values for snowmelt in 2001 were not used when calculating average values for these watersheds. Low estimates of runoff in these basins is believed to be responsible for these questionable values.

The next point of discussion is the difference between Niagara Creek and Mauze Gulch. Every year the ratio of runoff/precipitation is lower in Niagara Creek than Mauze Gulch. As stated earlier, these watersheds are comparable in size, slope, elevation gain, aspect, and permafrost content. The main difference between the two is that Niagara Creek has been affected by a tundra fire and contains a small percentage less shrubs than Mauze does. Every year there is lower flow/unit area in Niagara creek than Mauze Gulch. This could be the result of more water going into subsurface storage or more evapotranspiration. With part of Niagara being burned, there is less vegetation to transpire the water but more bare soil to evaporate the water. The affect of vegetation alone would produce the opposite effect of what the table shows.

Inspection of the specific discharge coupled with the water balance and recession analysis show that all data are consistent between watersheds. Although the basins vary in size, there are valid comparisons to be made using such analyses as specific discharge and the recession constants. From the above analyses we can start to quantify some of the differences that exist between watersheds with permafrost and those without. The specific discharge provides confirmation that baseflow exists in the watersheds with discontinuous permafrost and does not exist in continuous permafrost basins. The recession constants demonstrate patterns consistent with the existing literature, longer recession times in larger basins and longer recession times in permafrost basins. The runoff/precipitation ratios display differences between snowmelt and summer periods, where frozen ground is responsible for limiting infiltration into the subsurface. The summer r/p also tells us that the discontinuous basin, Clyde’s Gulch, is recharged by precipitation to a greater extent than Mauze Gulch and Niagara Creek. This is because water is able to move vertically through the subsurface in Clyde’s Gulch and not limited to horizontal flow by continuous permafrost.

HBV Model

In Table 11, the parameters and final values that were used when calibrating the HBV-96 model are summarized. The parameters where held constant in each watershed from year to year with the exception of the threshold temperature in Niagara Creek and the snow-melting factor in Clyde's Gulch. A discussion for these parameters is discussed in the appropriate section for each basin.

Table 11. Summary of parameters used in calibration of the HBV-96 model.

Parameter	Mauze Gulch	Niagara Creek	Melsing Creek	Clyde's Gulch
snow melting factor (mm/degree day)	6.5	7	4	2.5, 5.5
threshold temperature (°C)	1	1, 2	0	-2
water holding capacity	0.1	0.2	0.1	0.1
refreezing factor	0.05	0.05	0.05	0.1
field capacity (mm)	28	32	60	125
limit of evaporation	1	0.9	1	0.5
beta -exponent for drainage from soil	0.1	1	0.5	3
k4 - recession coeff for lower response box	NA	NA	0.5	0.1
percolation to groundwater (mm/day)	0	0	0.1	0.1
k0 -top coeff for upper response box	0.15	0.2	0.2	0.2
k1 -second coeff for upper response box	0.04	0.05	0.06	0.001
k2 -third coeff for upper response box	0	0	0.02	0.02
uzl0 -lower limit for kO (mm)	28	32	30	50

The timing of snowmelt and the modeling of the snow ablation is an essential subroutine in the HBV-96 model that impacts the timing of the simulated hydrograph, and therefore, the fit of the model. The threshold temperature had a large influence on the timing of melt as did the snow-melting factor. The manual for the HBV model generally lists the threshold temperature as falling in the range between –1 and 1 °C. In this study some watersheds had the value as high as 2°C. In the case of the threshold temperature, although water melts at 0°C, there is only one location where temperature was measured in the field and this one temperature was used to provide temperature to the model, it may not have been representative of the entire basin. The discussion that follows will explain the impact that the threshold temperature had on the results in the basins that were modeled.

Evaporation is used in the soil moisture accounting routine and thus it was unjustified to have different values of potential evaporation from year to year although when assessing the model and the parameters that most influence the model, it was found that a better fit could be achieved if the potential evaporation rates were adjusted from year to year. It followed that in wet years, better results were found when the potential evaporation rates were set higher than in low precipitation years. This may reflect the conditions that in wetter years there is more water available to evaporate. In the final model structure, the potential evaporation rates were all set equal in each year for each watershed to keep the model structure as uniform as possible and to allow for future use of the model without having to recalibrate it. This indicates a more sophisticated routine for calculating evapotranspiration would have improved model results.

Table 11 illustrates where differences in the model structure occur between the basins. The important parameters that directly relate to the presence of permafrost are the field capacity and the percolation, with the k2 response coefficient being tied to the percolation parameter. A major finding of this study is that the model can be set up to represent the presence or absence of significant permafrost based on the use of the percolation parameter, which allows water to enter the model as groundwater. Another important finding is that the field capacity seems to reflect the varying amounts of permafrost in the model. The field capacity is much smaller for the basins with continuous permafrost (28 and 32 mm) than it is for the basins with discontinuous permafrost (60 and 125mm). To extend this finding further, these numbers would suggest that Clyde's Gulch (field capacity=125mm) has less permafrost than Melsing Creek (field capacity=60mm). The difference may be due to the relative size of the watersheds but without additional studies to confirm these findings it is hard to say for sure. It is clear that the difference in the field capacity is real since we see that the values in the

Kougarok basin are much smaller than the Council basins in spite of the relative size of the basins.

The following sections discuss the results of the hydrograph simulation from each individual basin. The results of the snowmelt ablation are provided the section on ablation comparisons. The model was calibrated to achieve a fit to the measured runoff data. The ablation is presented although is was not the focus of model calibration.

Clyde's Gulch

Clyde's Gulch is a watershed that was not possible to calibrate with one parameter set. It is always difficult when there is limited years if data. There were only two complete years of data to calibrate the model, while it is recommended that 5 years of data be used for model calibration. The third year of data was reserved as the test year. The calibrated model was used to back calculate SWE for 2002, when maximum SWE was not surveyed. Each year showed sensitivity to different model parameters and without having additional years of data it is impossible to discern how the watershed behaves over a larger period of time. In this case, only one parameter was changed between the two sets in order to keep the parameter sets as consistent as possible in order to achieve a reasonable fit to the data.

Snow melting factor is a value, in mm, of the amount of snow that can melt in a day, so it makes sense that some years more snow will melt faster than in other years. The snow-melting factor was found to have the greatest effect on model fit in Clyde's Gulch. When relating this to actual watershed response, it may be legitimate to have different values of snow melting factor for different years because this value is dependent on the climate during the time of melt. The model does not take into account the wind or the net radiation at the time of melt so correction from year to year may be important. There was no attempt made in this study to relate the wind or the net radiation to the snow-melting factor at the time of melt. When relating it to the model, changing this parameter effects the time of the melt and the volume. The field capacity could be adjusted to get a better fit but this was avoided to keep the model structure as consistent as possible and to keep the model physically representative of the system.

The model was tested on data from 2002. This seemed to be an anomalous year in this basin. When looking at the runoff/precipitation rations, 2002 showed a value of 0.54, which is much higher than the previous years when it was, 0.24 and 0.29. The initial snowpack water equivalent was calculated to be 375mm, much higher than Melsing Creek. It was stated earlier that the 2002 snowmelt flood in Clyde's Gulch was an abnormal event that stripped the banks of the vegetation that had been there for many years. The hypothesis as to this unusual event is that snowmelt occurred during a very short time in this small basin. The volume of melt water created by a rapid melt did not have time to infiltrate to the subsurface as it normally would, causing the runoff to occur in a short period of time. This resulted in creating a very large flood for this basin. The same effect was not seen in Melsing Creek because the travel time in Melsing Creek is much greater. The result of this event gives us an unusually high estimate of initial snowpack water equivalent when estimated by the HBV-96 model (375 mm). This value is thought to be much higher than the actual SWE. This demonstrates some of the difficulty of using models to represent a real system. This is a small basin and the quick response time may affect the ability of the model to reflect the true system. To address the question of the model being able to represent small basins, the model was run using hourly time increments. Discussion is presented in the following section on hourly model runs.

In general, the model performed well in this basin in spite of the abnormal 2002 season. This suggests that the model may perform well in a typical year but unusual events may not be easily accounted for in it's current structure. Figures 18-20 show the simulated and observed hydrographs for Clyde's Gulch. Table 12 is a summary of the model performance for each year.

Table 12. Clyde’s Gulch summary of HBV-96 model performance.

Clyde’s Gulch		
Year	R^2	Acc. Diff (mm)
2000	0.84	-9.2
2001	0.72	9.8
2002	0.92	25.5

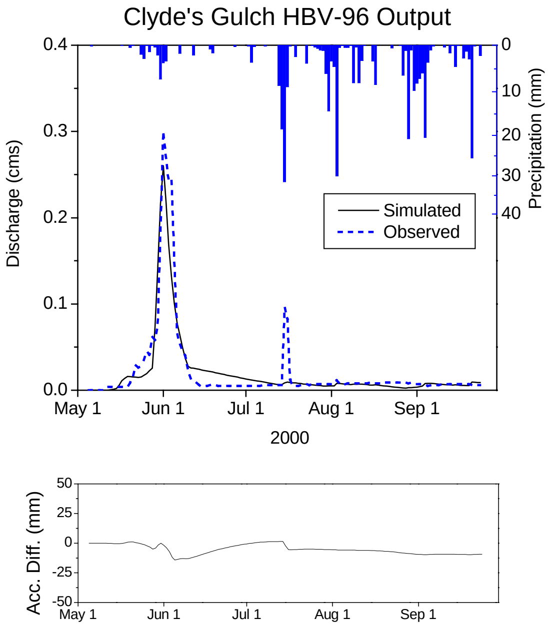

Figure 18. HBV-96 hydrograph output for Clyde’s Gulch 2000.

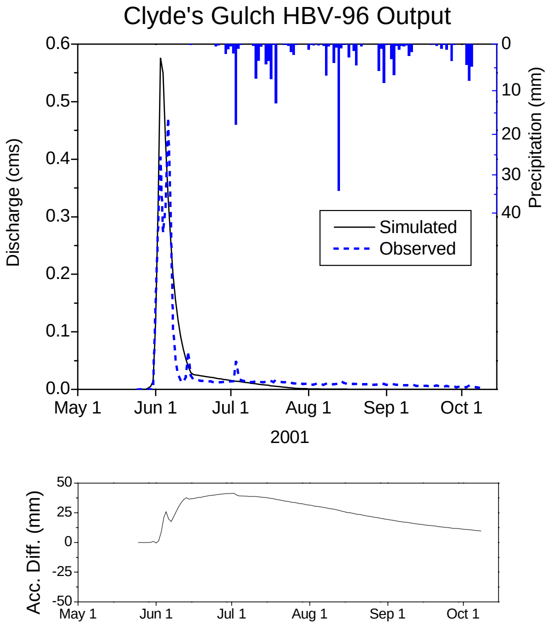

Figure 19. HBV-96 hydrograph output for Clyde's Gulch 2001.

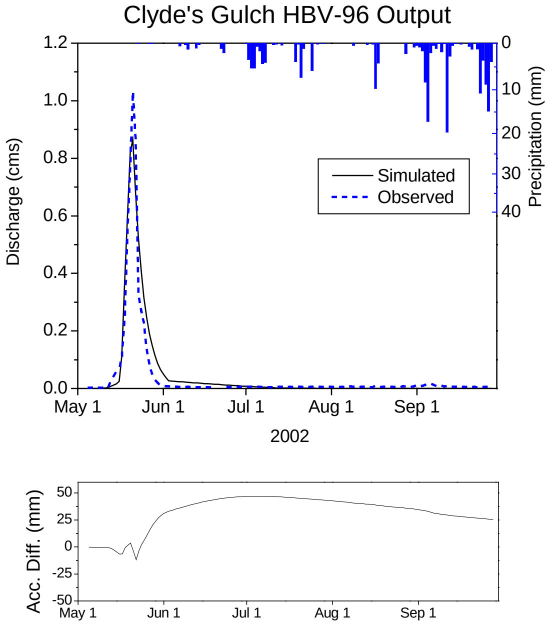

Figure 20. HBV-96 hydrograph output for Clyde's Gulch 2002.

Based on the criteria used for evaluating the model performance in this watershed, the model did very well at simulating the timing of melt and the magnitude of melt. The shape of the recession curve was not simulated well in 2000 and occasional rain events were not realistically simulated.

Melsing Creek

The HBV model was calibrated for the summers of 2000 and 2001. After achieving a reasonable fit for those two years it was tested on a third year (2002) and used to back calculate the initial values for SWE because a maximum SWE was not measured during spring 2002.

Melsing Creek has the most complete data set and is most like the watersheds that the HBV model was designed. The other watersheds in this study are significantly smaller than the HBV design watersheds. The consequence of this is that the results for this basin are very consistent and the same set of model parameters was shown to give good results in all years of data (Table 13).

Table 13. Melsing Creek summary of HBV-96 model performance.

Melsing Creek		
Year	R^2	Acc. Diff (mm)
2000	0.81	57.0
2001	0.81	-76.5
2002	0.94	-24.0

As part of the calibration procedure an adjustment of the potential evaporation was made in order to get a good fit with the low summer flows. If great fits for individual years were the goal, then adjusting the potential evaporation and the values of Beta could be done to achieve better results than simply using one parameter set. This was not the goal or intention of the project. In Melsing Creek, the year 2000 model overestimated the amount of baseflow, while it underestimated baseflow in 2001. The model parameters were adjusted until the model over-predicted accumulated difference in 2000 by roughly the same amount it under-predicted in 2001. The soil moisture was also held constant for each year (30mm) in the initial state. Small improvements could be made to the model by changing this value but by examining the soil moisture data from year to year, it was prudent to assume the same pre-melt value. Model outputs are shown for Melsing Creek in Figures 21-23.

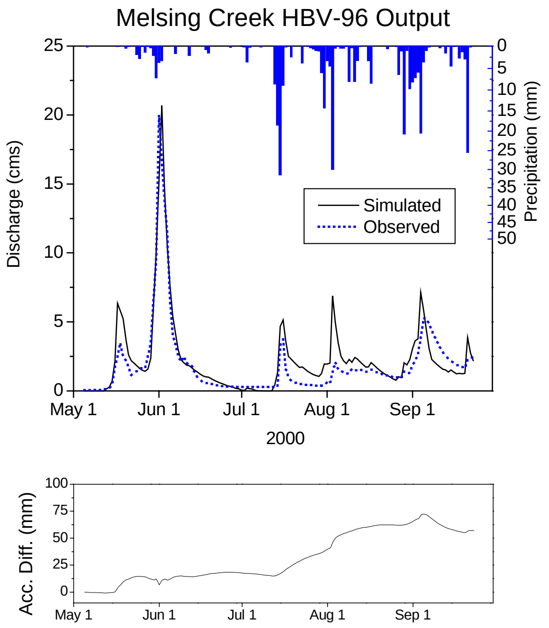

Figure 21. HBV-96 hydrograph output for Melsing Creek 2000.

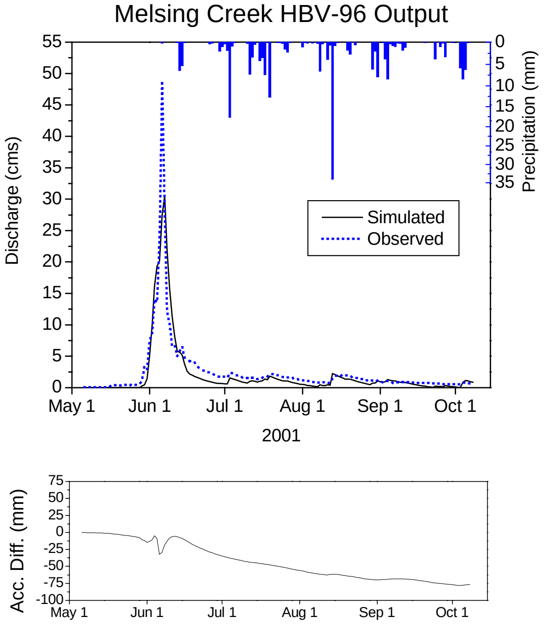

Figure 22. HBV-96 hydrograph output for Melsing Creek 2001.

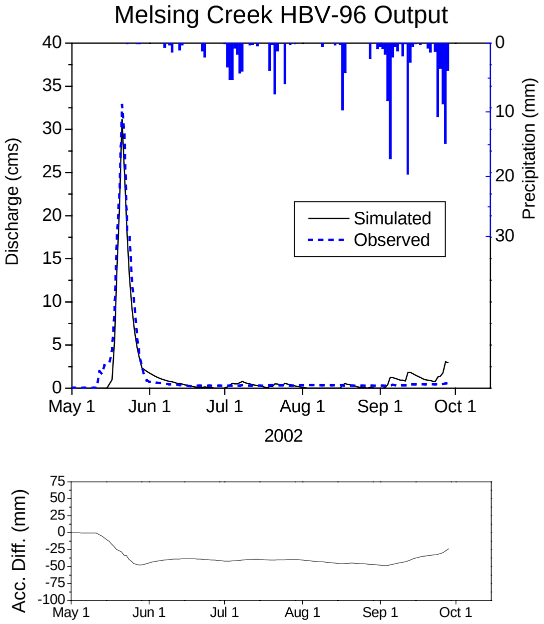

Figure 23. HBV-96 hydrograph output for Melsing Creek 2002.

In Melsing Creek, the test year, 2002 had astonishing results with and R^2 of 0.97. The temperature and precipitation data were input into the model along with an estimate of the winter SWE. The good model fit can be attributed to the fact that the initial SWE was adjusted in order to achieve a good model fit. Whether the predicted SWE is representative of the true system is debatable, especially given the discrepancy seen between the SWE in Melsing Creek and Clyde's Gulch, which should have been close to the same.

The baseflow component of the model compared well with observed values for each year but slightly overestimated the baseflow in 2002. The frequency and quantity of rainfall is largely related to how the model simulates runoff. Different parameters are responsible for routing water in the soil moisture routine depending on whether dry or wet conditions exist. Different parameters in the model control the runoff component depending on whether the rain has been constant, filling up the soil moisture zone, or if the rain followed a sustained dry event. Many years of data are needed in order to calibrate the model for a variety of conditions and this may be one reason that the model did not simulate the baseflow well in the test year.

Mauze Gulch

Three years of data were used to calibrate the model for Mauze Gulch (1999, 2000, and 2001). A fourth year, 2002 was reserved as a test year and subsequently used to calculate a maximum SWE. A single parameter set was not found to give adequate results for this creek, but was held constant nonetheless. In an effort to keep the parameters uniform one set was found to work well for 2000 and 2001 but gave very poor results for 1999 (R^2=-0.42) (Table 14). In this case the SWE was scrutinized. Using the same parameter set for 1999 yielded a modeled snowmelt that was much greater than the recorded snowmelt. The onset of melt was closely approximated and the late summer baseflow was modeled well but because of the large difference in spring runoff peaks, the model performed poorly for this year. The only way to force the model to make the measured values for spring flow was to adjust the SWE. There is reason, based on the water balance calculations to question the SWE for

1999. The SWE in 1999 was much higher than the other years but the peak flood did not correspond to the high SWE. Unfortunately, we do not have a record for the Council sites to compare the SWE for 1999.

Table 14. Mauze Gulch summary of HBV-96 model performance.

Mauze Gulch		
Year	R^2	Acc. Diff (mm)
1999	-0.42	38.9
2000	0.88	6.5
2001	0.79	10.9
2002	0.81	11.3

The model consistently predicted the onset of melt within a day or two and the peaks within a day or two (Figures 24-27). In 1999 and 2002, the simulated runoff receded after the measured flow and in 2001 and 2000 it receded before. The baseflow was simulated very well in 2000 (Figure 25) and late summer 1999 (Figure 24). These are all periods when there was sustained precipitation. The model does not perform well for small summer storms when the soil is likely dry, such as early summer 1999, the simulated baseflow goes to 0 cms while the measured stream still has flow.

Once the model was calibrated it was run for the 2002 test year and back calculated the SWE at 126mm.

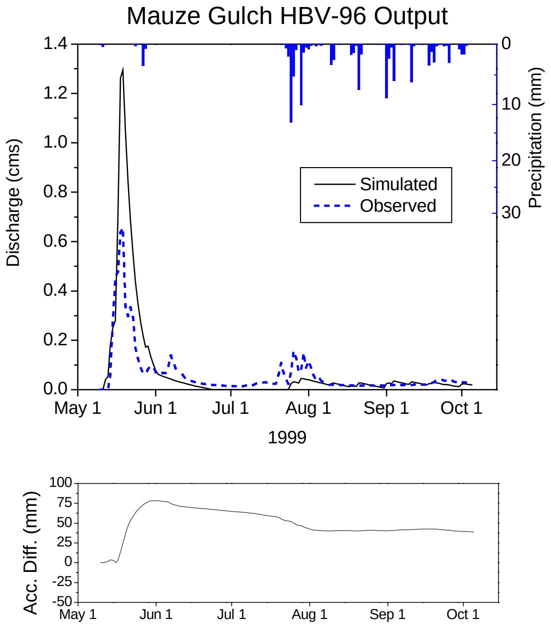

Figure 24. HBV-96 hydrograph output for Mauze Gulch 1999.

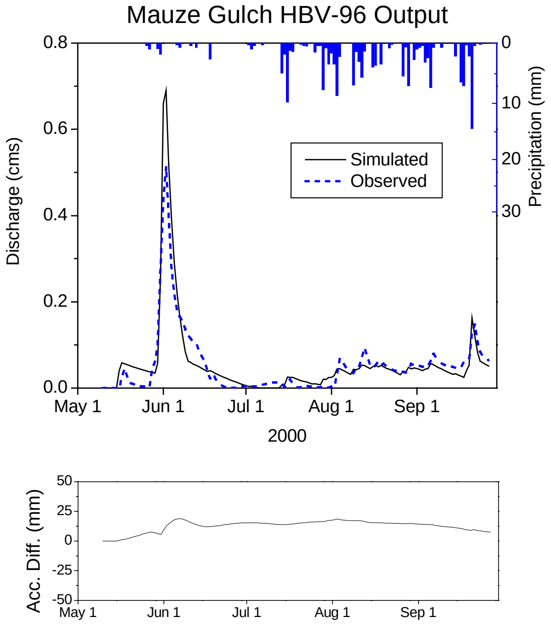

Figure 25. HBV-96 hydrograph output for Mauze Gulch 2000.

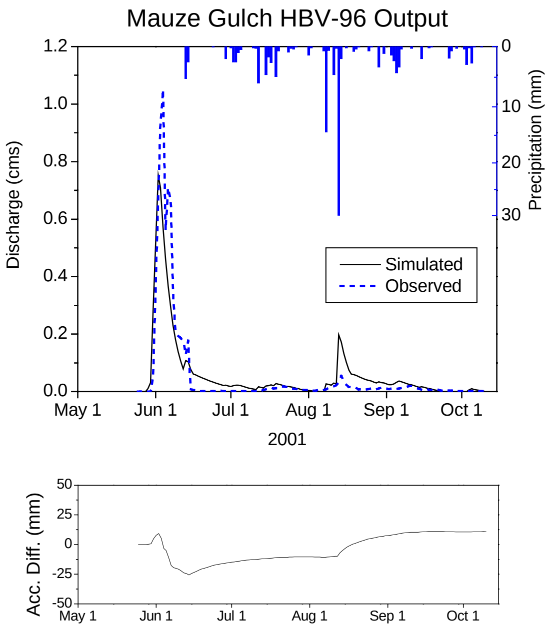

Figure 26. HBV-96 hydrograph output for Mauze Gulch 2001.

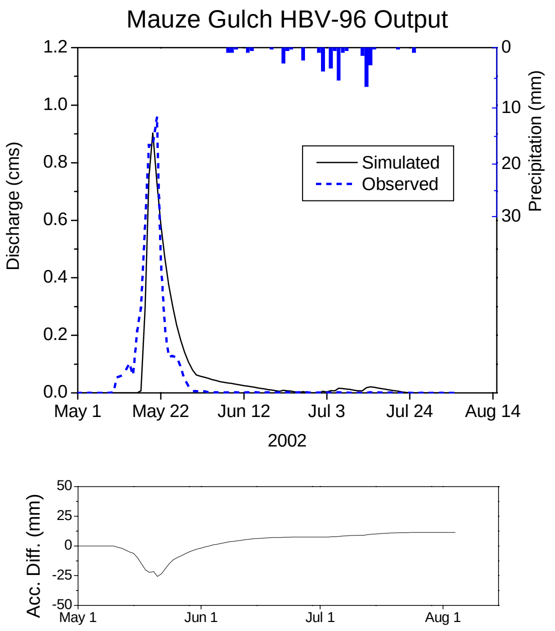

Figure 27. HBV-96 hydrograph output for Mauze Gulch 2002.

Niagara Creek

The model was run for Niagara Creek with three years of data (1999, 2000, and 2001). As with the other watersheds, 2002 was reserved to test the model and use it to calculate the pre-melt SWE. The model was first run using the parameter set from Mauze Gulch on the assumption that the two streams would act very similar. The model was examined for it's sensitivity to parameter changes and one parameter was chosen to limit the differences. In Niagara Creek the threshold temperature and field capacity were the most influential in reproducing the observed flows well, but the field capacity was held constant. The threshold temperature was changed in this watershed in order to get the timing of melt simulated well.

It was seen in Mauze Gulch that 1999 proved to be an anomalous year when attempting to simulate the snowmelt hydrograph. The same scenario was seen in Niagara Creek in 1999. A run of the model in 1999 provided an R^2 =-2.42. Other years were much more acceptable (Table 15). The reason for the negative R^2 is that the volume of runoff during snowmelt was much larger in the simulated hydrograph than the observed hydrograph; the possible reason was discussed in the previous section. Figures 28-31 show that the timing of the onset and timing of the peak of snowmelt were simulated within a couple of days of the observed timing.

Table 15. Niagara Creek summary of HBV-96 model performance.

Niagara Creek		
Year	R^2	Acc. Diff (mm)
1999	-2.42	26.4
2000	0.48	15.8
2001	0.9	15.4
2002	0.95	13.3

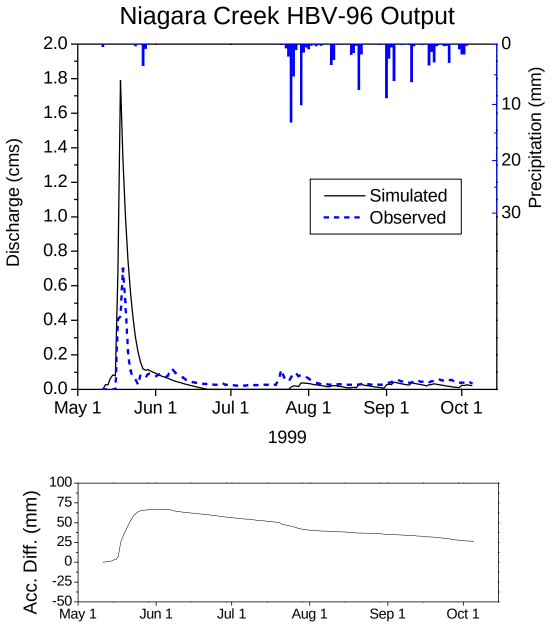

Figure 28. HBV-96 hydrograph output for Niagara Creek 1999.

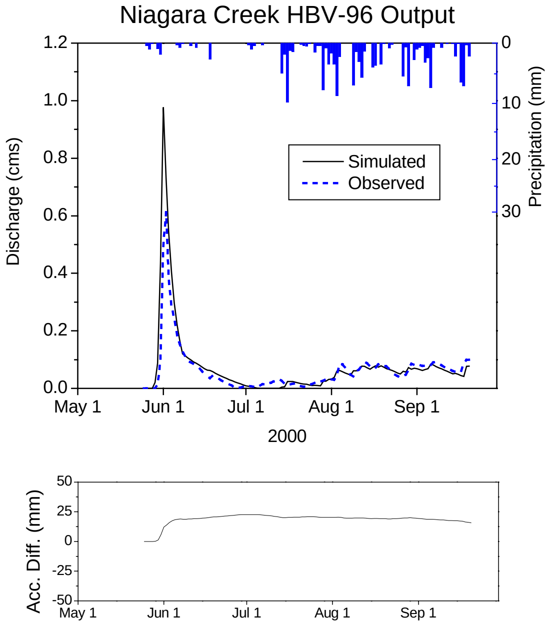

Figure 29. HBV-96 hydrograph output for Niagara Creek 2000.

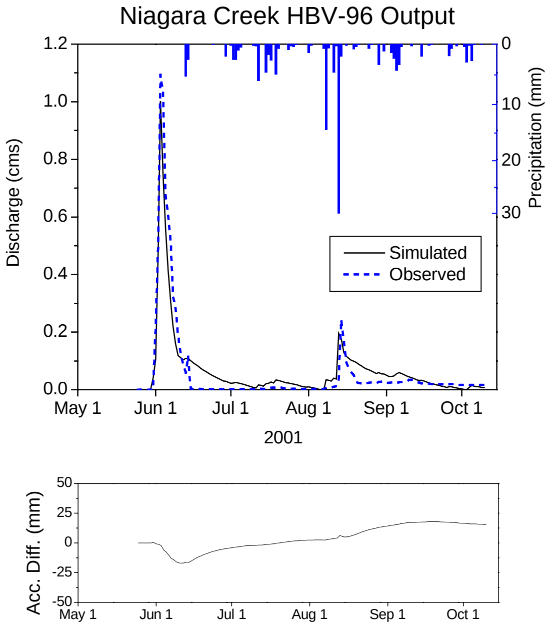

Figure 30. HBV-96 hydrograph output for Niagara Creek 2001.

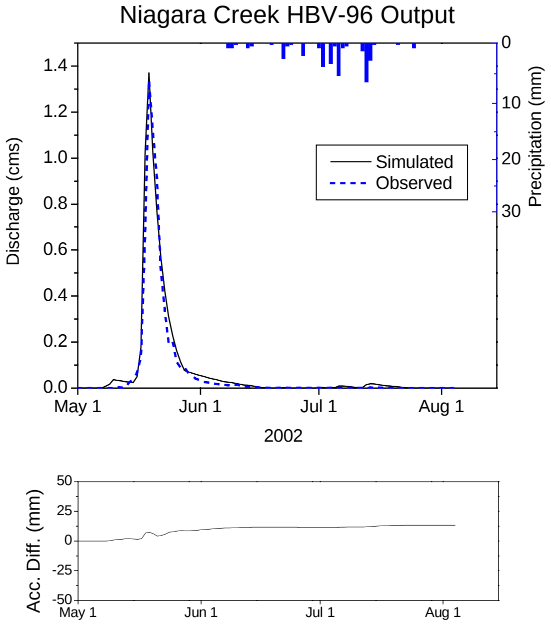

Figure 31. HBV-96 hydrograph output for Niagara Creek 2002.

The model output for 1999 and 2000 clearly show that the estimate of the snowmelt runoff is much higher than the measured runoff. Because we see the same difference in both watersheds in Kougarok, we question the estimate of SWE in 1999. In general, the model responded to precipitation well, especially in 2000. The 2000 season was closely modeled for baseflow. This indicates that the model performs well when rain has fallen steadily throughout the summer and the soil is mostly saturated. In 1999, a rain event occurred in late July that was not simulated well because there was little rainfall before the storm event and the soil was drier. As seen before, without many years of data to calibrate the model, it is difficult to understand the variability of the natural system and how it behaves over time and apply that understanding to modeling.

Hourly Model Runs

The HBV-96 model was designed to use average daily values but is capable of running on smaller time steps. The HBV-96 model was developed in watersheds that are not underlain by permafrost. The HBV-96 was developed and tested on subbasins with a typical area of 40 km^2, but is capable of being run on basins of any area (Lindström et al., 1997). This means that the design watersheds generally have more attenuated processes than the small watersheds that were studied near Kougarok. The smaller watersheds that contain permafrost typically have quick response times and it was felt that the model may not have accurately accounted for these processes when executed with daily values. Ablation was not modeled as effectively as was hoped. It is important to note that the model was calibrated based on the runoff and the parameters used to model snowmelt were not the focus of calibration, but rather an ancillary indication of model performance. Ablation can vary significantly from day to day, hour to hour, depending on the temperature, wind and radiation. A daily temperature average was hypothesized to be insufficient to accurately model ablation. Analysis was done to assess the models sensitivity to the time increments of the input data. The model is capable of running on hourly time steps and by using hourly data, we expected to more accurately model the runoff and ablation in the smaller watersheds in Kougarok.

Two watersheds were chosen to test the models sensitivity to using smaller time increments, Mauze Gulch and Melsing Creek. The 2000 season was chosen based on the quality of the data and belief that this was a typical year hydrologically. One small watershed (Mauze Gulch) was chosen to contrast the larger watershed (Melsing Creek) in order to evaluate what affect using smaller time steps had on model performance in watersheds that had very different hydrologic characteristics.

Small differences were seen in the hydrographs when run using daily vs. hourly data (Figures 32-33). The model showed a slight decrease in performance using the hourly data. Mauze Gulch was displayed a slightly lower value for R^2, with and R^2=0.86 executed on hourly time steps and 0.88 executed on daily time steps. The R^2 for Melsing using hourly time steps was 0.79 and was 0.81 using daily time steps.

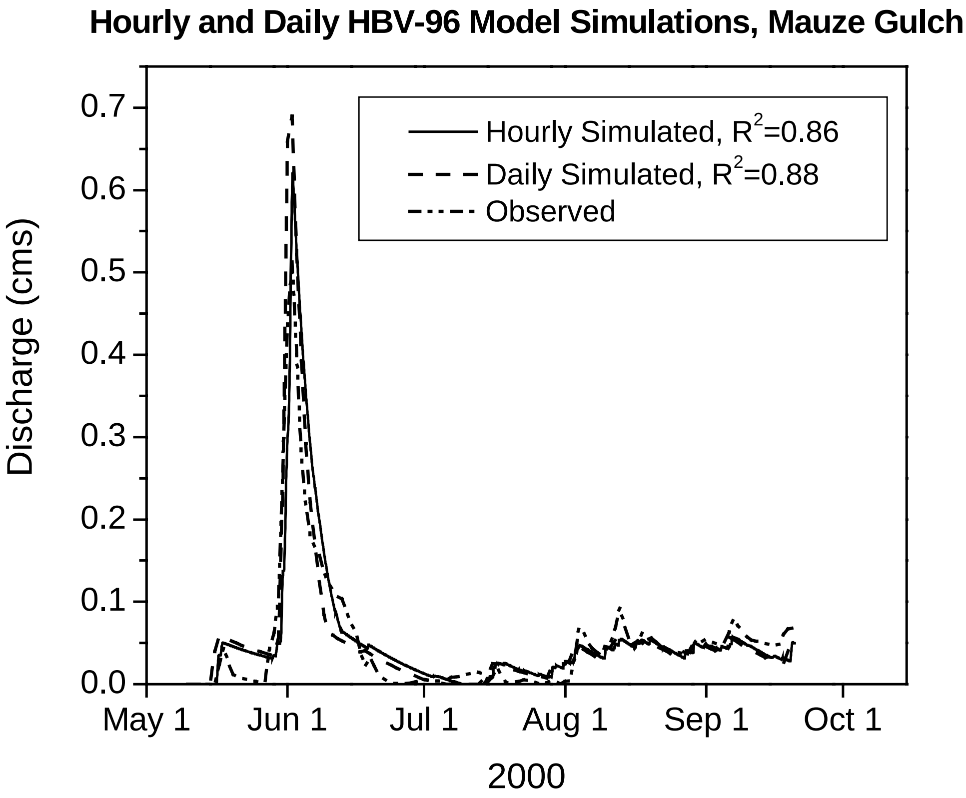

Figure 32. Mauze Gulch comparison of hourly and daily HBV-96 simulations.

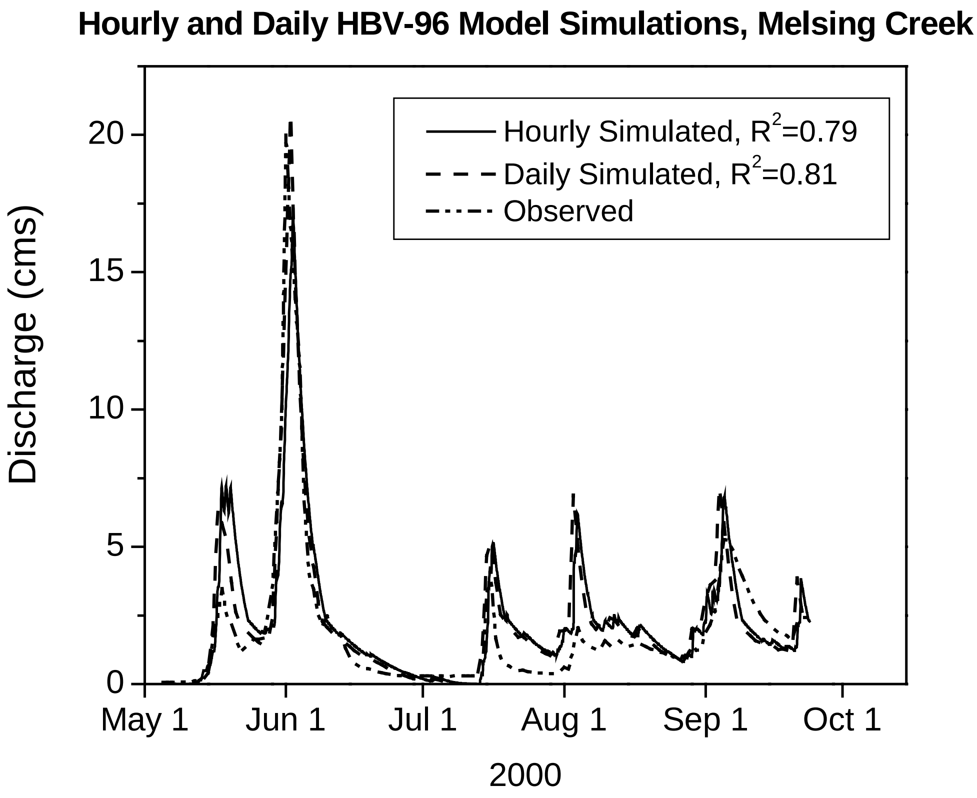

Figure 33. Melsing Creek comparison of hourly and daily HBV-96 simulations.

There was not much difference seen between the hourly and daily modeled ablation (Figures 34-35). Hinzman and Kane (1991) stated that a simple degree day method was inadequate to accurately model snowmelt since the melt was also largely influenced by radiation, convection, and other factors not accounted for in a degree day formula.

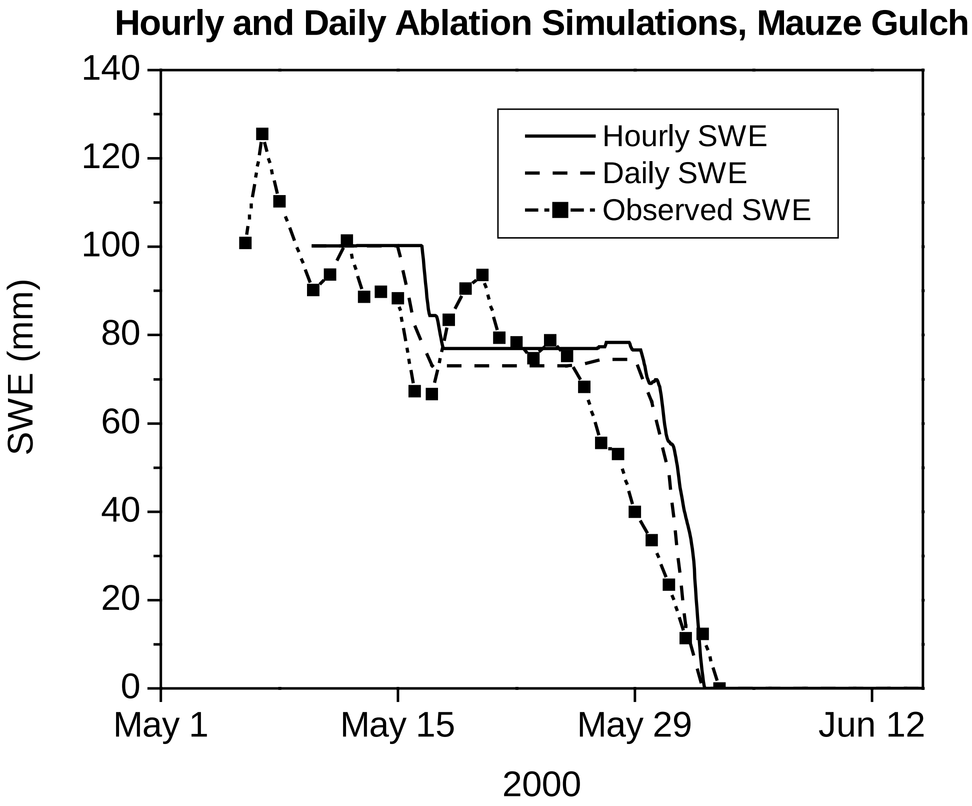

Figure 34. Mauze Gulch comparison of hourly and daily HBV-96 ablation simulations.

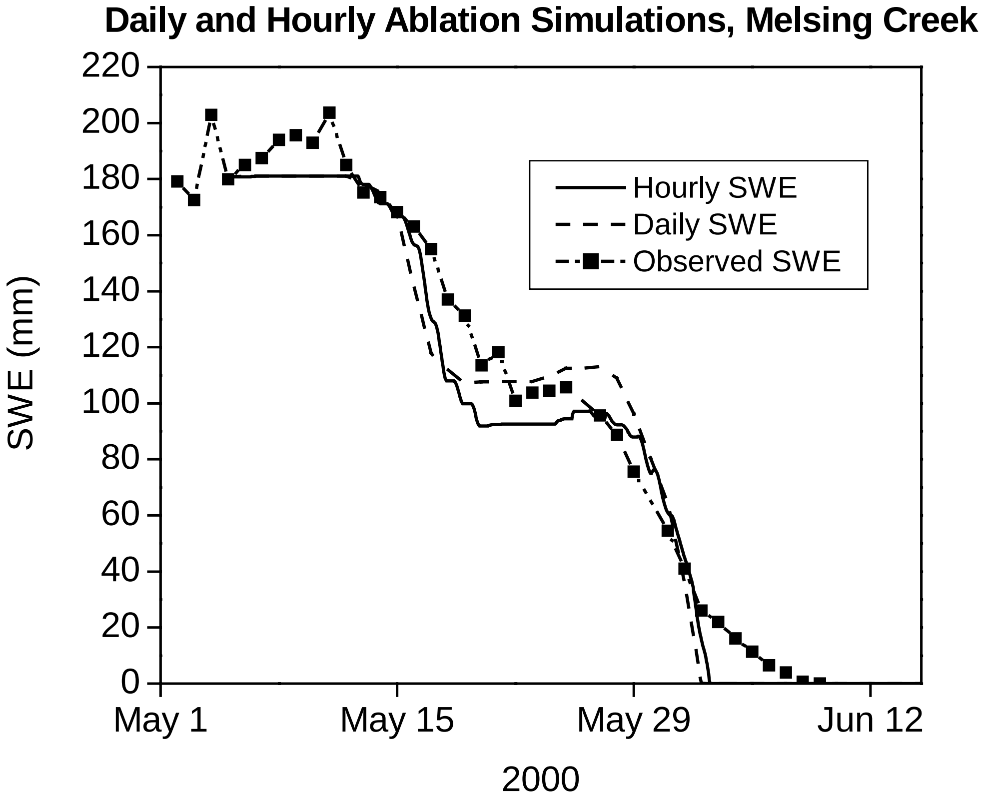

Figure 35. Melsing Creek comparisons of hourly and daily HBV-96 ablation simulations.

Hinzman and Kane (1991) used the HBV model in the Imnavait Creek watershed (Figure 1) and found that the model performance was not improved using 2-hour time steps vs. daily average time steps. Five years of data were run in Imnavait Creek, slight improvement was reported in three years the model was executed and slight decreases were seen in the R^2 in two years of model simulations. The Imnavait Creek watershed is underlain by continuous permafrost and is smaller than the Kougarok watersheds (2.2 km^2). The findings from this thesis and previous studies in Imnavait Creek support findings that the model performs adequately using daily values of temperature and precipitation in these types of watersheds.

Model Comparisons

In general, the model performed well for all the watersheds, but worked significantly better for the Council watersheds. In all watersheds, values of $R^2>0.8$ were achieved for at least half of the model executions. Watersheds with baseflow are more stable and have longer response times than watersheds that do not have baseflow, a consequence of being underlain by permafrost. The greater stability of the watersheds in Council is likely responsible for the ability to model these basins with better results. The HBV-96 model performed well in the basins in Kougarok for 3 out of 4 years in Mauze Gulch and 2 out of 4 years in Niagara Creek. The 1999 measured SWE in Kougarok was determined to be unrepresentative of the true system. Taking this year into account, the model performed very well for the basins in Kougarok also.

The model structure is able to represent different basin characteristics. In the Council watersheds, the percolation parameter was used to simulate the groundwater component of the hydrology. The field capacities were also higher in the watersheds in Council, which corresponds to a deeper active layer in these watersheds that are not continuous permafrost.

The model was developed for Scandinavian watersheds that, in general, are larger than the watersheds were examined. On average, the subbasins that the HBV-96 model was designed and calibrated for averaged 40 km^2 (Lindström et al., 1997). Three of the watersheds in this study were much smaller than 40 km^2 and this may factor into the model performance. It was observed that the model did poorly with short response times and the size of our watersheds may be the reason. The model was run on a daily time steps and hourly time steps in order to determine if a shorter time step could improve the model fit. It was determined in both Melsing Creek (a large watershed) and Mauze Gulch (a small watershed) that executing the model using hourly time increments did not help improve the results.

The measured SWE proved to be a very important factor when calibrating the model and when assessing the model fit. As it has been discussed previously, snowmelt is the dominant hydrological event of the year. This carries through to the modeling efforts where it was shown that estimates of SWE had the most impact on the R^2 for the year. This does not necessarily mean that the model poorly represents the watershed but it does mean that the initial state of the model needs to be carefully understood. It was seen in both Mauze Gulch and Niagara Creek that the model drastically over-predicted the runoff during snowmelt in 1999. It was shown that there is reason to believe that the maximum SWE in 1999 was a high estimate since the same response in the model was seen in both creeks in Kougarok in 1999, and the SWE for 1999 was significantly higher than any other year. Obtaining a basin wide SWE is difficult to accurately measure based on the variability of the snowpack across the basin and the redistribution of the snow that occurs. It is important that data collection is carefully planned out when attempting to assess the maximum SWE of an entire basin. Limitations of using one number to represent a basin average needs to be understood when executing runoff models during the snowmelt period.

Comparisons Across Alaska

The HBV model has been used in watersheds across Alaska that contain varying amounts of permafrost. Part of this study was to assess the HBV model's ability to capture the influence of the amount of permafrost based on the parameters that were used to calibrate the model. Interesting results were seen by comparing the two parameters, field capacity and percolation, which reflect the influence permafrost has on the model performance. Previous studies using the HBV model have been done in the Imnavait watershed (Hinzman and Kane, 1991) (2.2 km^2) located on the North Slope of Alaska (Figure 1), and in the C2 (5.2 km^2), C3 (5.7 km^2), and C4 (11.4 km^2) watersheds located in the Caribou Poker Creek Research Watershed, CPCRW (Figure 1) near Fairbanks Alaska (Knudson and Hinzman, 2000). Braun and Renner (1992) applied the HBV model to five watersheds in Switzerland. The HBV model was found to be adequately applied to various basins but indicated that no definite relationships could be found relating basin characteristics and parameter values. They felt that the sample size was too small and possibly the model was not suited to reflect differences.

Table 16 is a summary of the watersheds across Alaska and the parameters that reflect the permafrost content in the HBV model. The watersheds are listed in order of decreasing extent of permafrost. The watersheds on the Seward Peninsula showed a trend that related the extent of permafrost to the field capacity; as permafrost extent increases, field capacity decreased. Table 16 demonstrates that this trend is also seen in the watersheds that were studied by Hinzman and Kane (1991) and Knudson and Hinzman (2000). The percolation parameter also displays the trend that in general, the greater the extent of permafrost, the lower the percolation. Note, percolation is 0 in all watersheds that are continuously underlain by permafrost.

Table 16. HBV model parameter comparisons in watersheds across Alaska.

	Imnavait Creek	**Mauze Gulch**	**Niagara Creek**	**Melsing Creek**	**C3**	**Clyde's Gulch**	**C4**	**C2**
% Permafrost	100	100	100	50	53.2	20	18.8	2.5
Area (km^2)	2.2	4.9	6.5	80.6	5.7	2	11.4	5.2
Field Capacity (mm)	30-40	28	30	60	220	125	190	220
Percolation (mm/day)	0	0	0	0.1	0.8	0.1	4	19

Previous modeling results from watersheds across Alaska and findings in this study support the conclusion that the HBV model can reflect physical differences between watersheds. The varying extent of permafrost has a large affect on the physical hydrology. The previous study by Braun and Renner (1992) focused on watersheds that had subtle differences between them. They main physical differences between the watersheds that were studied in Switzerland varied in elevation, percent forest cover, and percent glaciation. The differences between the watersheds in Switzerland were not so extreme to cause the physical differences to be reflected in the model parameters. The distribution of permafrost and the thickness of the active layer, which is largely responsible for the value of the field capacity parameter, has a large influence on the optimum model parameters. Permafrost also has an influence on the area that is available for water to enter the physical groundwater system. The ability of water to enter the groundwater system is reflected in the percolation parameter and shows the physical differences that exist between watersheds based on the permafrost content.

Ablation Comparisons

A brief discussion of the ablation is provided in order to assess the overall performance of the model. The model calculated an ablation curve based on the initial SWE that was input into the model. The values used for the initial SWE came from the data collected during the initial survey of the basin of maximum SWE. The observed ablation curves were obtained from the weighted average values obtained daily from field studies. Therefore, the simulated ablation curves from the model and the observed (measured) curves are not the same. In 2002, field crews started monitoring snowmelt after the snowpack had started to ablate and an estimate of maximum SWE was obtained in 2002. In the previous years a basin snow survey was conducted earlier in the spring in order to obtain a better estimate of the maximum SWE. The measured and simulated curves may not correlate well to each other but comparing the timing of the measured and simulated ablation is valuable when assessing the performance of the model (Figures 36-39).

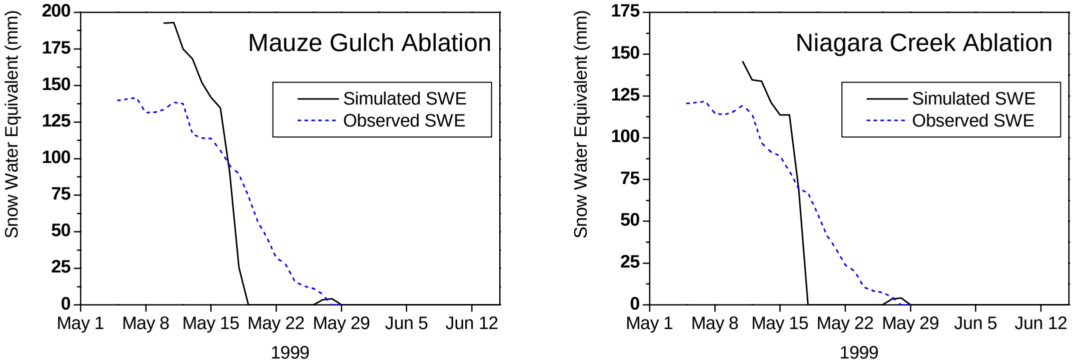

Figure 36. HBV-96 ablation curves for 1999.

It can be seen in the ablation curves for 1999 that the initial SWE is much higher in the simulated curve compared to the observed curve. The simulated melt was much quicker than the observed and may contribute to the large volume seen in the simulated hydrograph. The bias in the observed sites contributes to the large difference seen in the timing. Sites were chosen and monitored where snow remained even after much of the watershed had already ablated. The simulated curve is essentially melting one site to completion without taking into account the variability across the watershed.

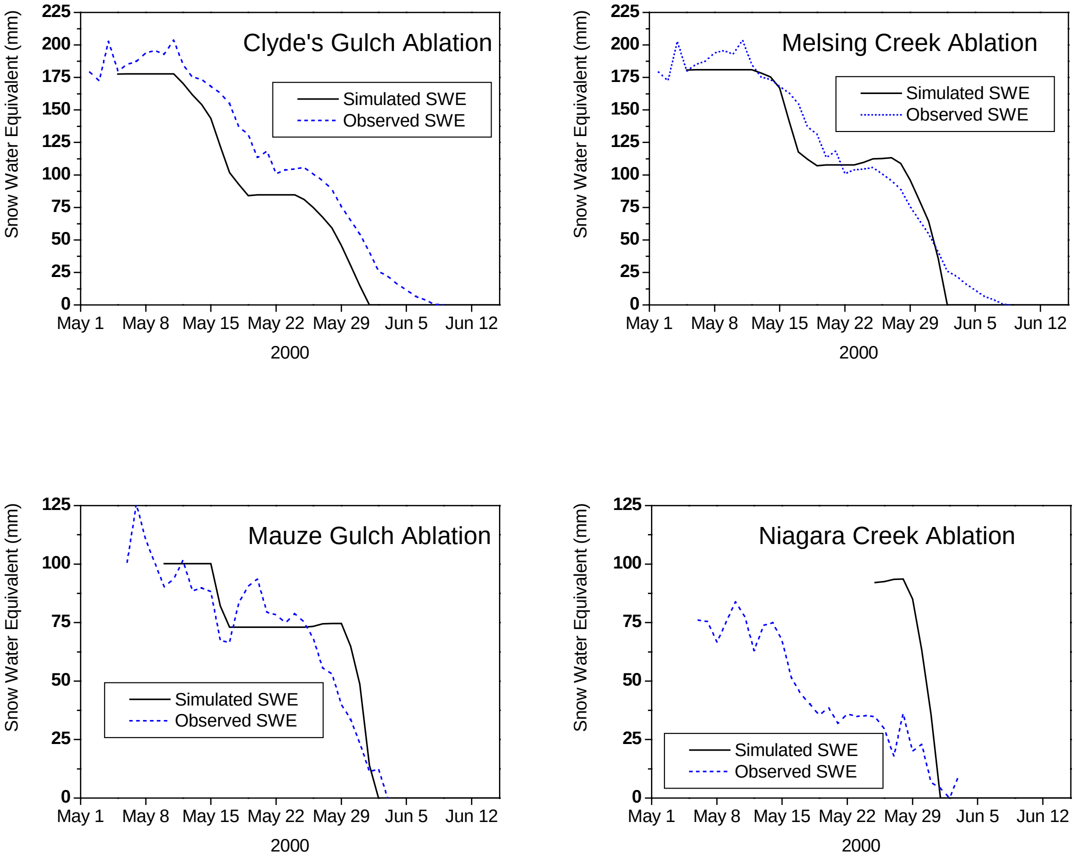

Figure 37. HBV-96 ablation curves for 2000.

The ablation curves for 2000 (Figure 37) show that the model predicted the shape of the curves well for the Council sites but the simulated timing was early by a few days. The warming and cooling trend can be seen in both the simulated and observed ablation curves. The Mauze Gulch watershed showed similar trends in the melt, with a period of cold weather shown by an interruption in the melt.

It would be expected that the model would simulate the melt in Niagara much the same as it did in Mauze Gulch but the poor simulation of melt is attributed to the water holding capacity of the snow being different. The water holding capacity of the snow was set at 0.2 in Niagara Creek and 0.1 in Mauze Gulch. The model does not allow water to drain from the snowpack and contribute to runoff until the water holding capacity (proportion of water content/snowpack) is reached. This effectively delays the timing of ablation and runoff because the more of the snowpack needs to melt before the water is allowed to runoff. Runoff due to snowmelt is initiated later in Niagara Creek than Mauze Gulch every year (Figures 7,9,11,and 13). To force the model to fit the true timing of runoff, it was necessary to use the water holding capacity to delay melt. This caused the simulated ablation curves to occur later than the measured curves in Niagara Creek. The difference in size of the drainage basins and the distribution of vegetation are both believed to be the physical mechanisms responsible for the difference in the timing of melt. Niagara Creek is a larger watershed and the travel time for this watershed is longer.

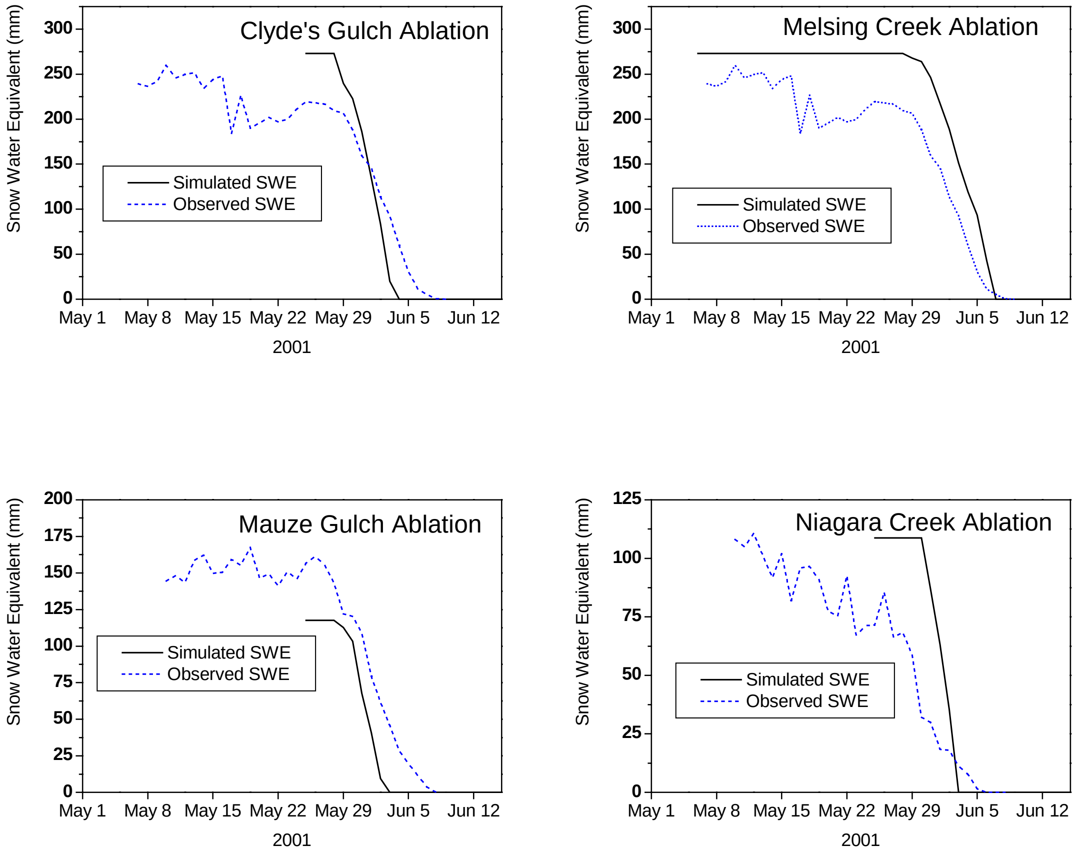

Figure 38. HBV-96 ablation curves for 2001.

The ablation curve in Niagara shows the same trend as the previous year where the melt was delayed and then the snowpack was simulated to ablate quickly. Melsing Creek is the only watershed in this year to adequately simulate the completion of melt. It is important to stress again, that the location of the measurements is an important factor when comparing it to a models prediction, which does not take into account the various vegetation types. Also, the observed curves are lower in some cases due to the methods of data collection discussed previously.

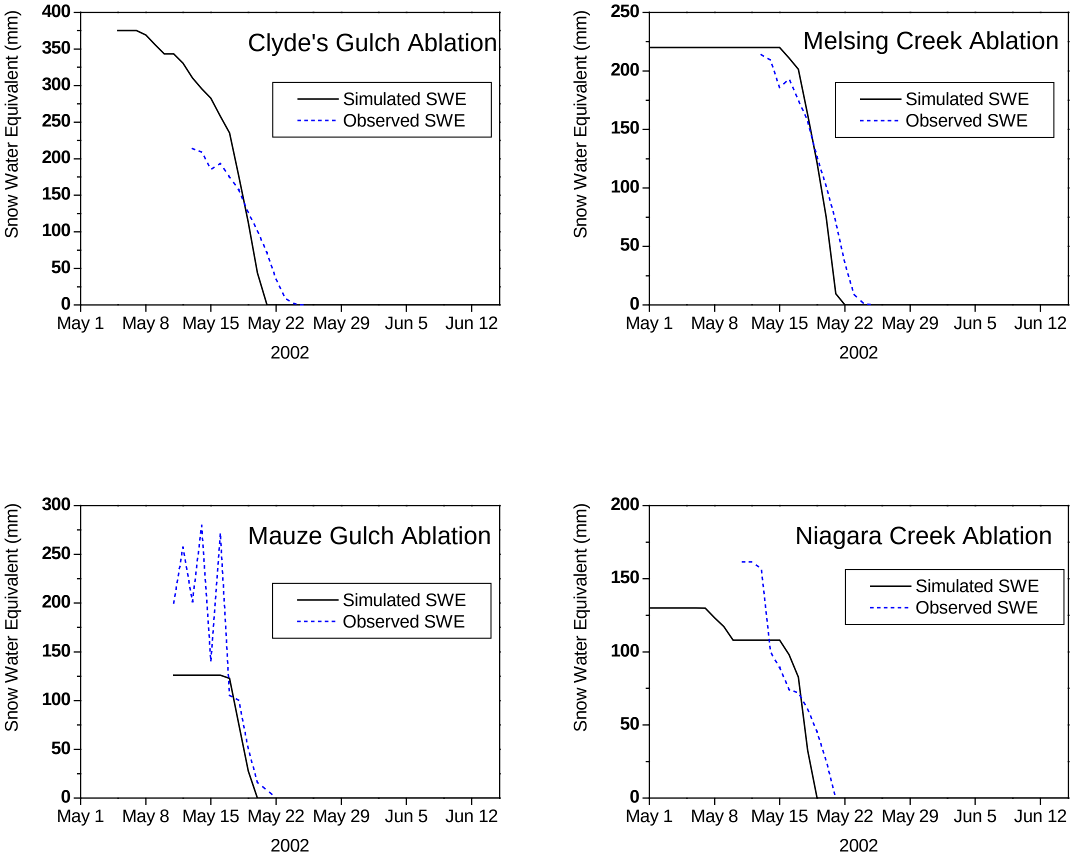

Figure 39. HBV-96 ablation curves for 2002.

The 2002 model test year yields interesting results. Melsing Creek performed the best of all the watersheds. Clyde's Gulch graphically illustrates the abnormal spring melt flood that occurred by showing the difference between the observed data and the simulated curve which is much greater than is believed to represent the system. Conversely, Niagara Creek did not demonstrate the quick ablation as seen in previous years. The timing of completion of melt is the most closely modeled in 2002 and was seen to ablate within 3 days of the observed completion. Bias in data collection sites is demonstrated in Mauze Gulch and Niagara Creek. Field crews did not start measuring ablation until a large part of the snow pack had already ablated. This would mean that the observed curves theoretically should start with a SWE lower than the simulated sites. The contrary is seen because field crews chose sampling sites where the snow was deep, in order to measure the ablation, even though much of the watershed was already void of snow when measurements were started.

CONCLUSION

The hydrology of four basins on the Seward Peninsula was studied and compared using traditional hydrological analysis and computer modeling. In addition, the results of the HBV-96 model were compared to sites previously studied in Alaska using the HBV model. The objective of the study was to determine if differences in the extent of permafrost distribution in a basin would be reflected in physical hydrologic response and computer modeling. It was shown that the rainfall/runoff ratios, specific discharge, and recession constants did illustrate physical differences between the basins. The HBV-96 computer model also reflected the differences between the basins in the parameters percolation and field capacity. Comparisons with past applications of the HBV model across Alaska showed that the HBV model was successful in reflecting the differences between basins containing varying extents of permafrost was not limited to the ones studied on the Seward Peninsula, but trends were applicable across Alaska.

The SWE was found to be a large source of uncertainty when attempting to quantify the hydrology of the basins. A large discrepancy was seen between the SWE that was calculated by the model in 2002 in Melsing Creek and Clyde's Gulch, which should display a similar snowpack. The observed value of SWE was also concluded to be high in the Kougarok basins in 1999. More years of data are needed to calibrate the model to reflect the yearly variations in the natural system.

The model performed much better in Melsing Creek than the other watersheds because the flow is more stable and the response times are slower due to its size. The model was tested for its ability to more accurately estimate the measured runoff in small watersheds by executing it with hourly time increments. Results showed that hourly time increments did not improve the model fit when compared to model execution using daily time increments.

In conclusion, the hydrologic response in watersheds with continuous and discontinuous permafrost can be distinguished by studying the physical hydrology of a basin and by executing a runoff model such as HBV-96. The hydrologic components of rainfall/runoff ratios, specific discharge, and recession constants all reflected the difference between continuous and discontinuous permafrost in the study basins. The parameters for percolation and field capacity in the HBV model can be used to differentiate basins with continuous permafrost and basins with varying amounts of discontinuous permafrost.

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APPENDIX A

Hydrographs

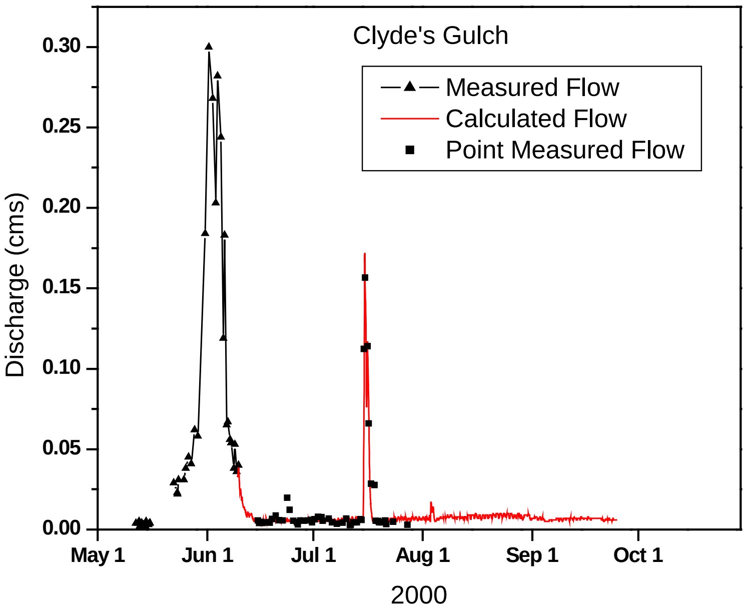

Figure 40. Clyde’s Gulch Hydrograph for 2000.

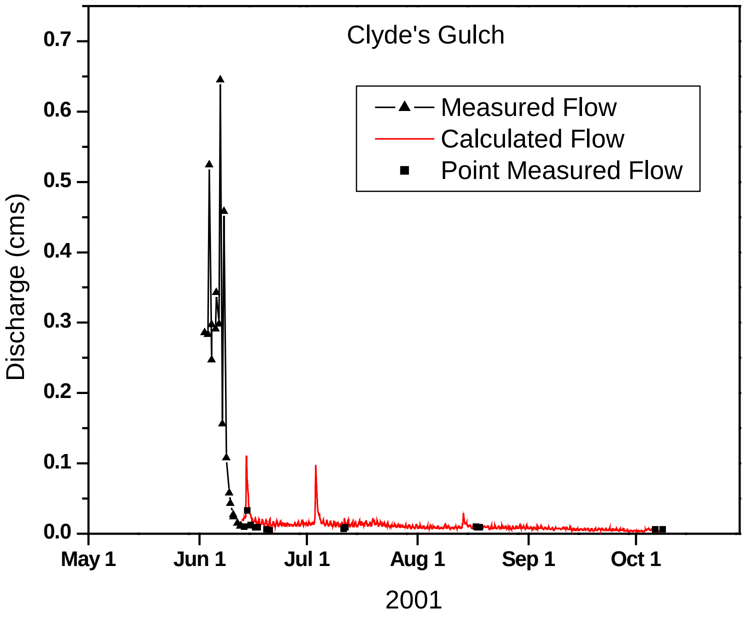

Figure 41. Clyde's Gulch Hydrograph for 2001.

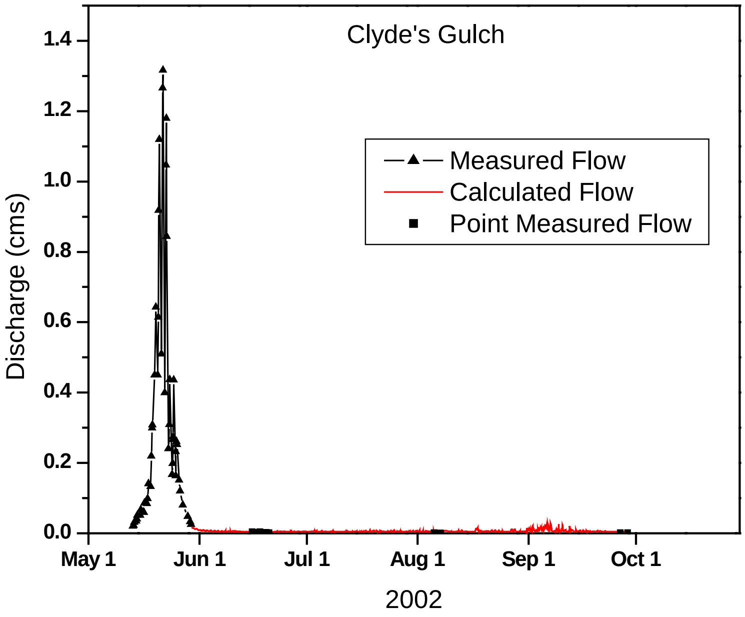

Figure 42. Clyde's Gulch Hydrograph for 2002.

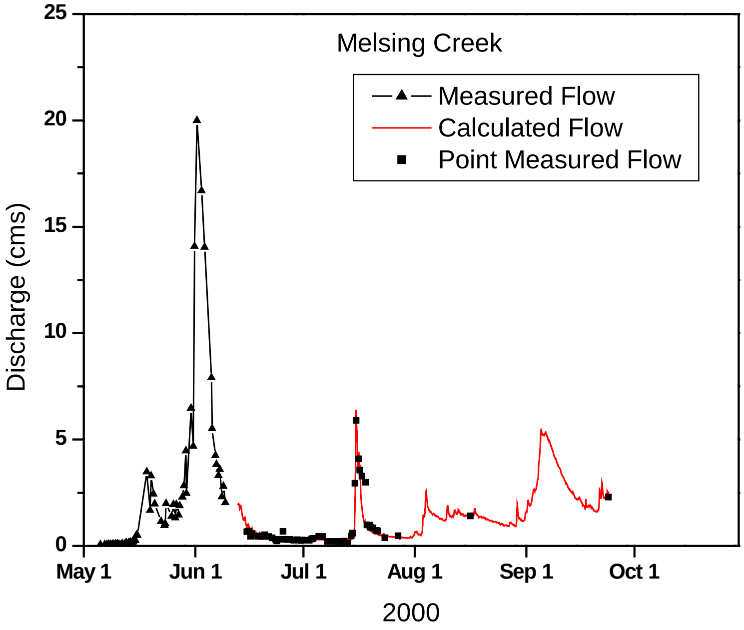

Figure 43. Melsing Creek Hydrograph for 2000.

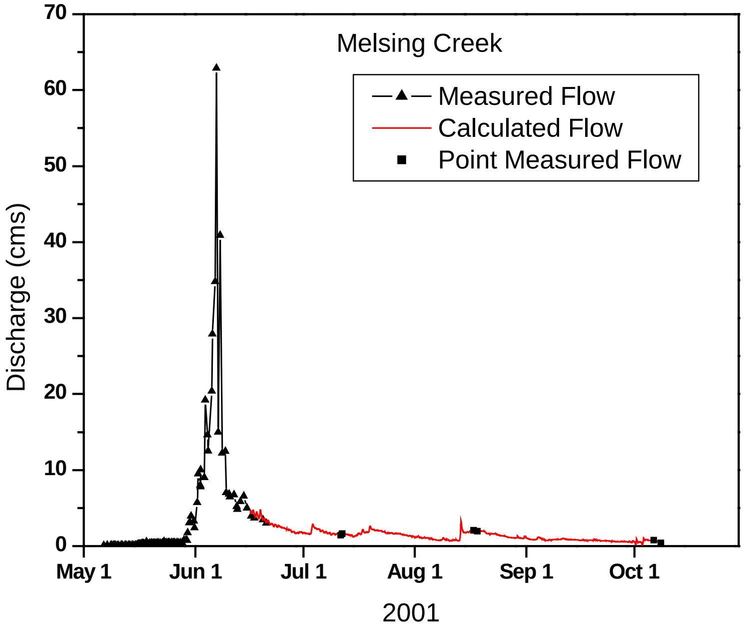

Figure 44. Melsing Creek Hydrograph for 2001.

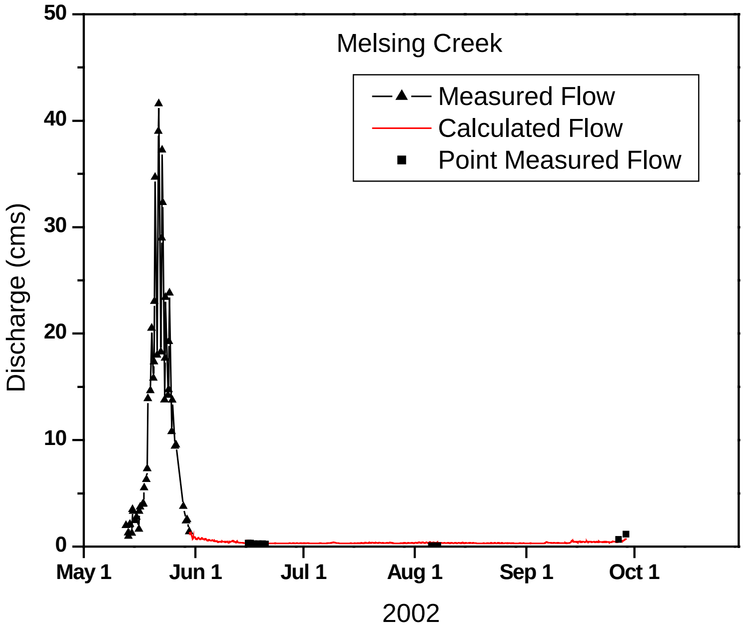

Figure 45. Melsing Creek Hydrograph for 2002.

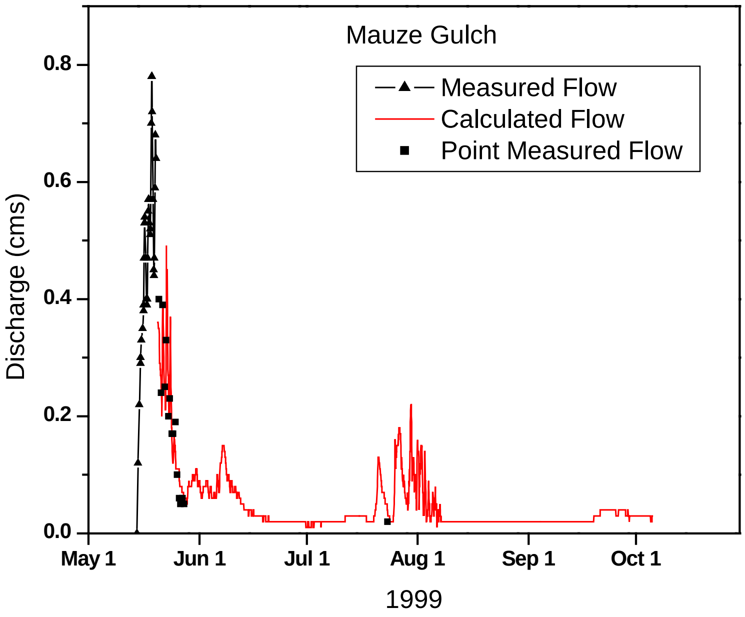

Figure 46. Mauze Gulch Hydrograph for 1999.

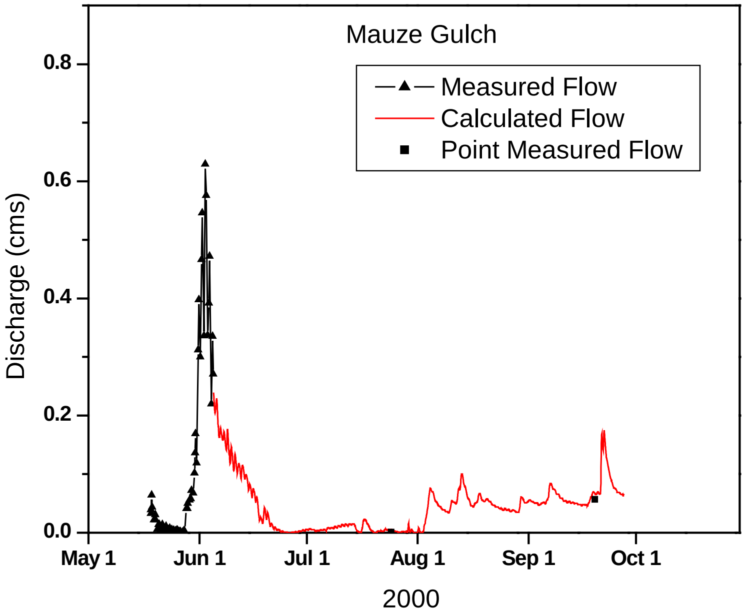

Figure 47. Mauze Gulch Hydrograph for 2000.

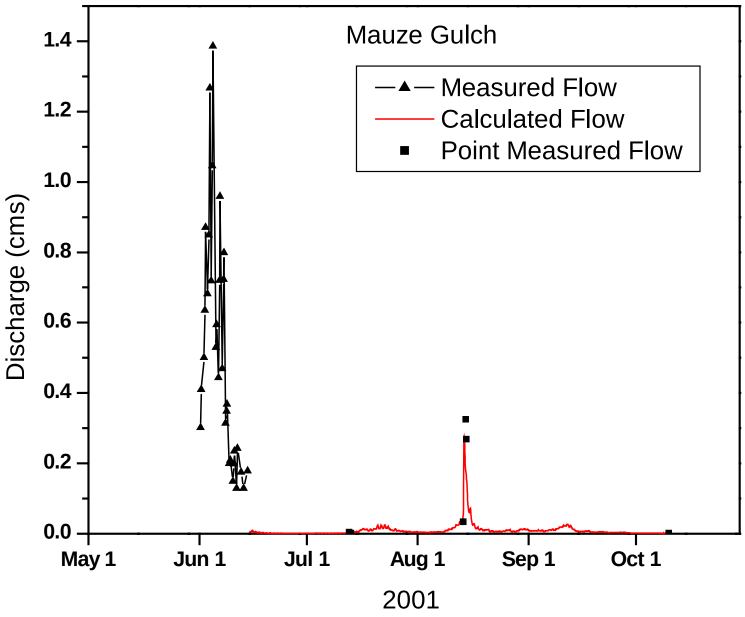

Figure 48. Mauze Gulch Hydrograph for 2001.

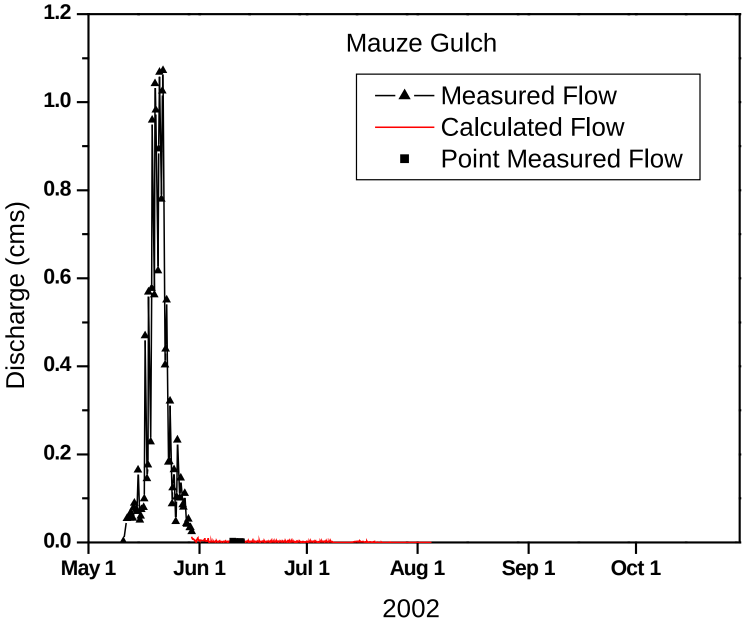

Figure 49. Mauze Gulch Hydrograph for 2002.

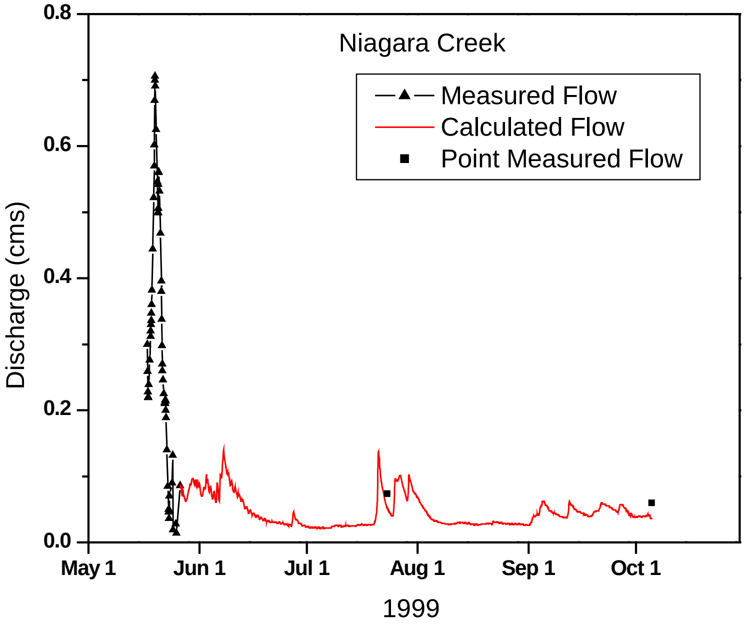

Figure 50. Niagara Creek Hydrograph for 1999.

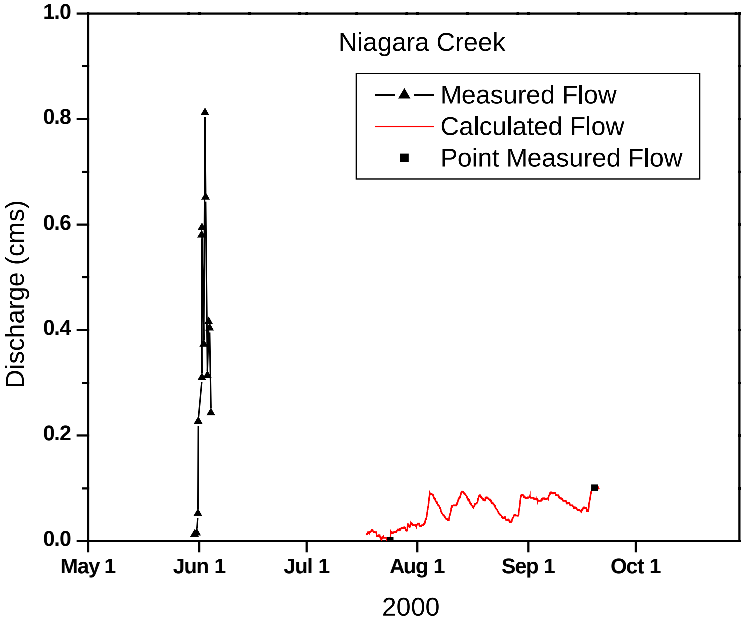

Figure 51. Niagara Creek Hydrograph for 2000.

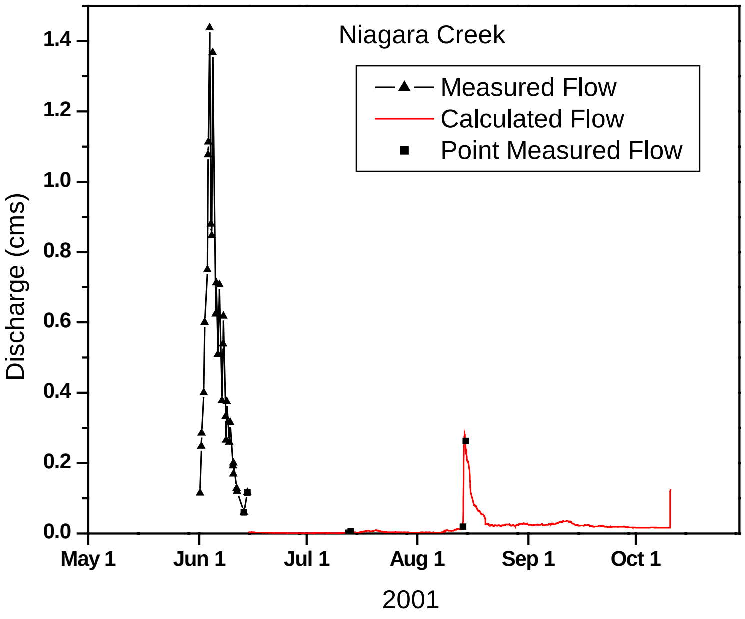

Figure 52. Niagara Creek Hydrograph for 2001.

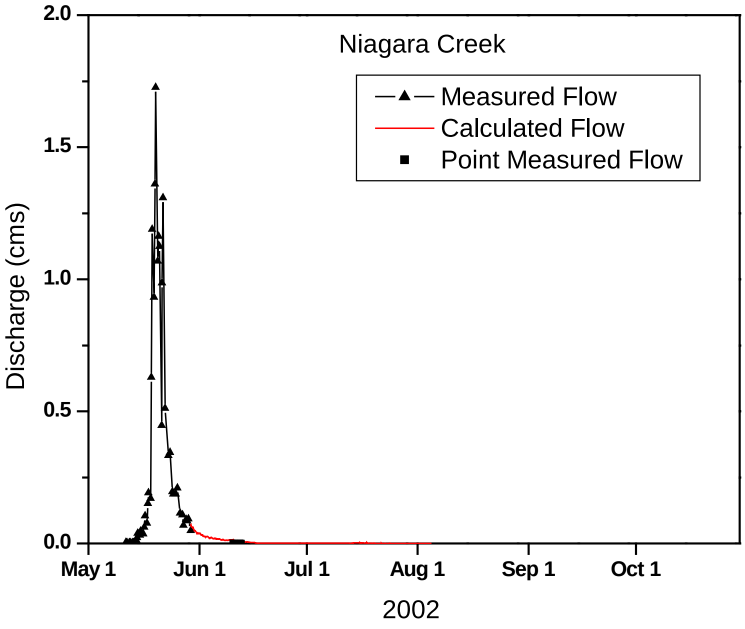

Figure 53. Niagara Creek Hydrograph for 2002.

APPENDIX B

HBV-96 Model Output

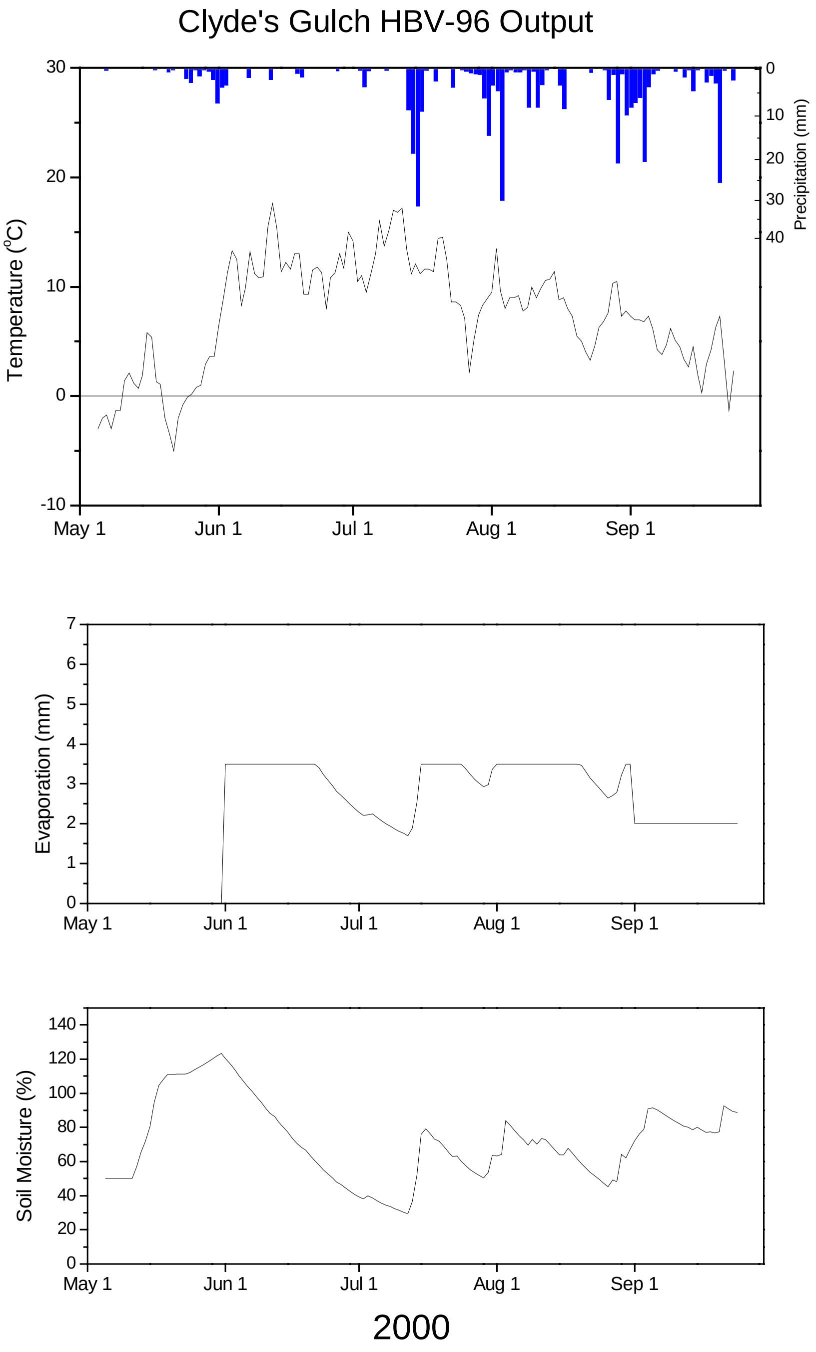

Figure 54. HBV-96 Model Output for Clyde's Gulch 2000.

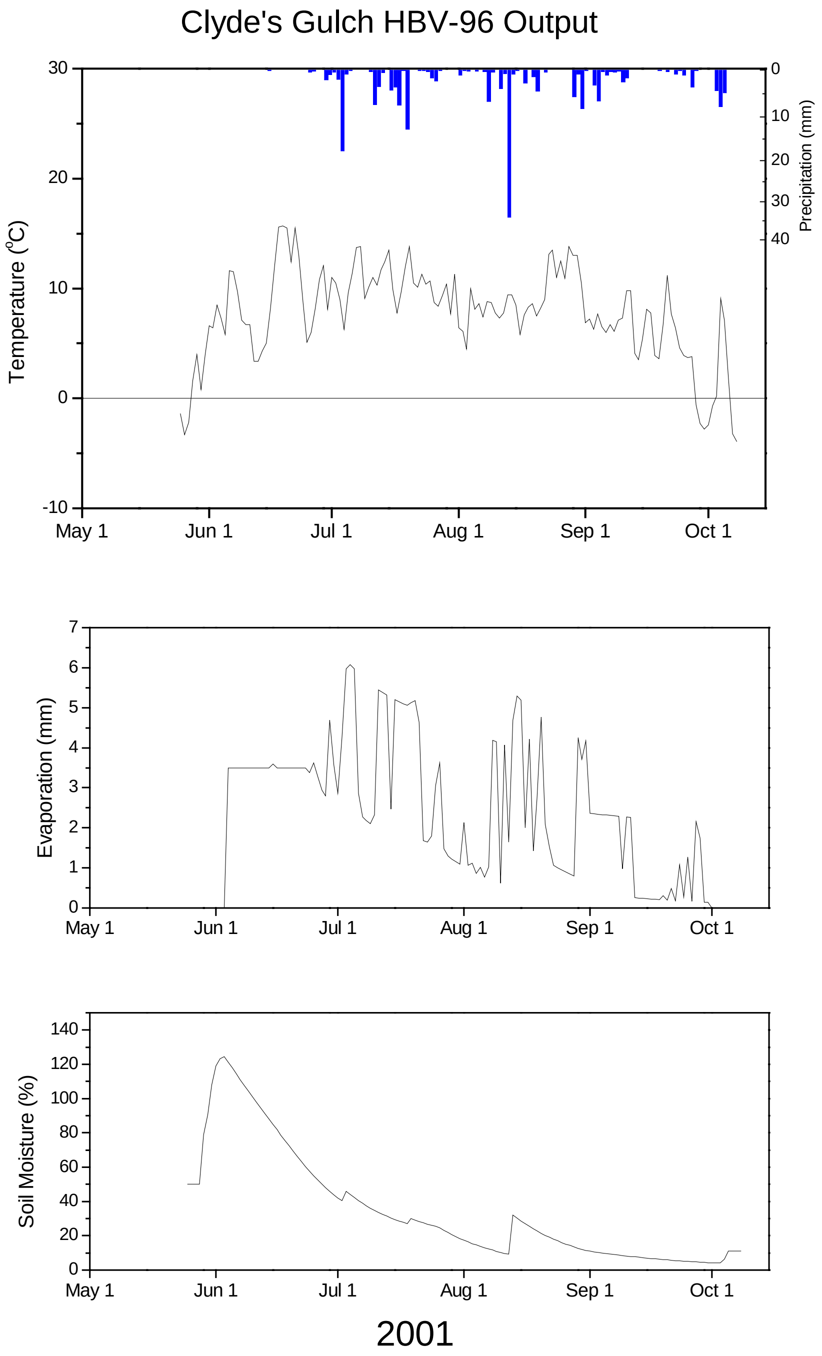

Figure 55. HBV-96 Model Output for Clyde's Gulch 2001.

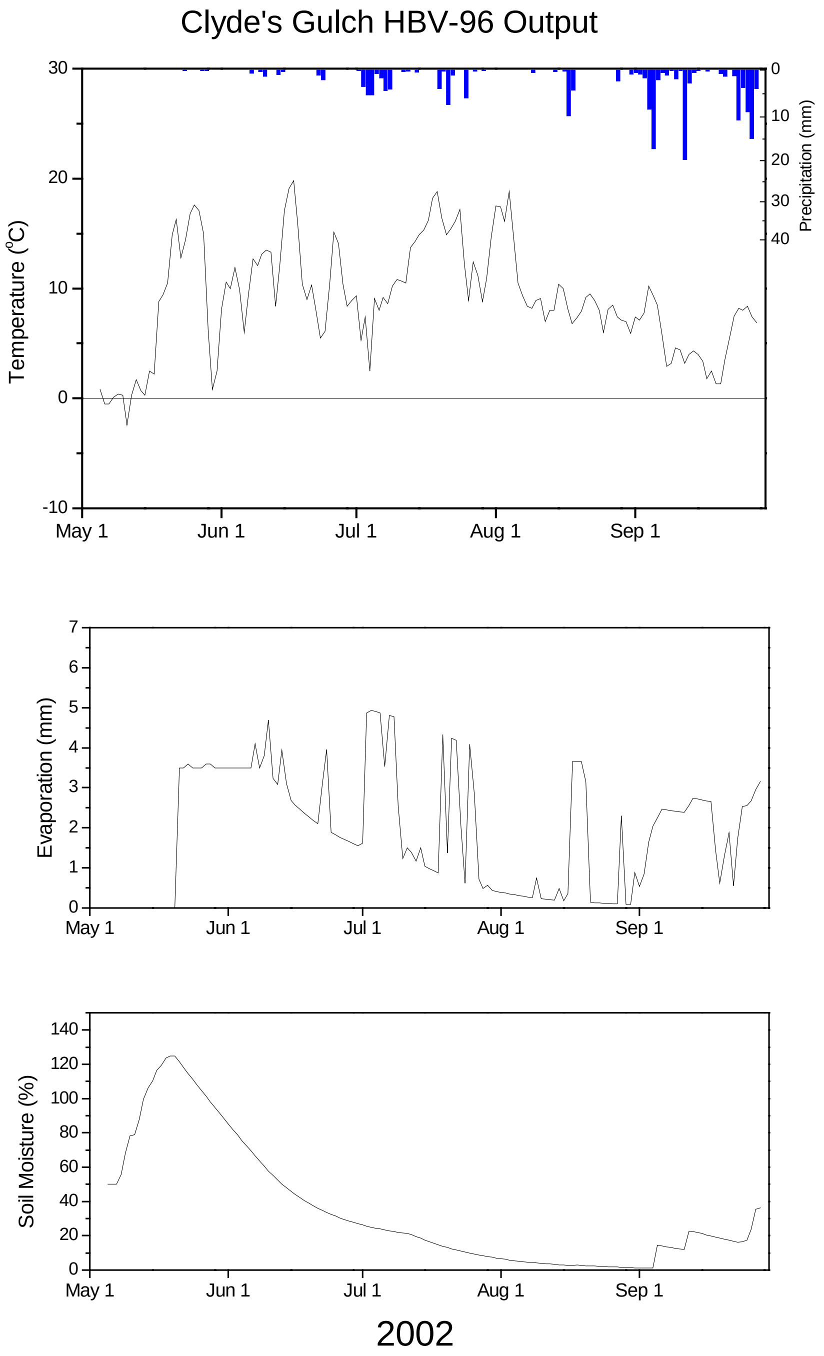

Figure 56. HBV-96 Model Output for Clyde's Gulch 2002.

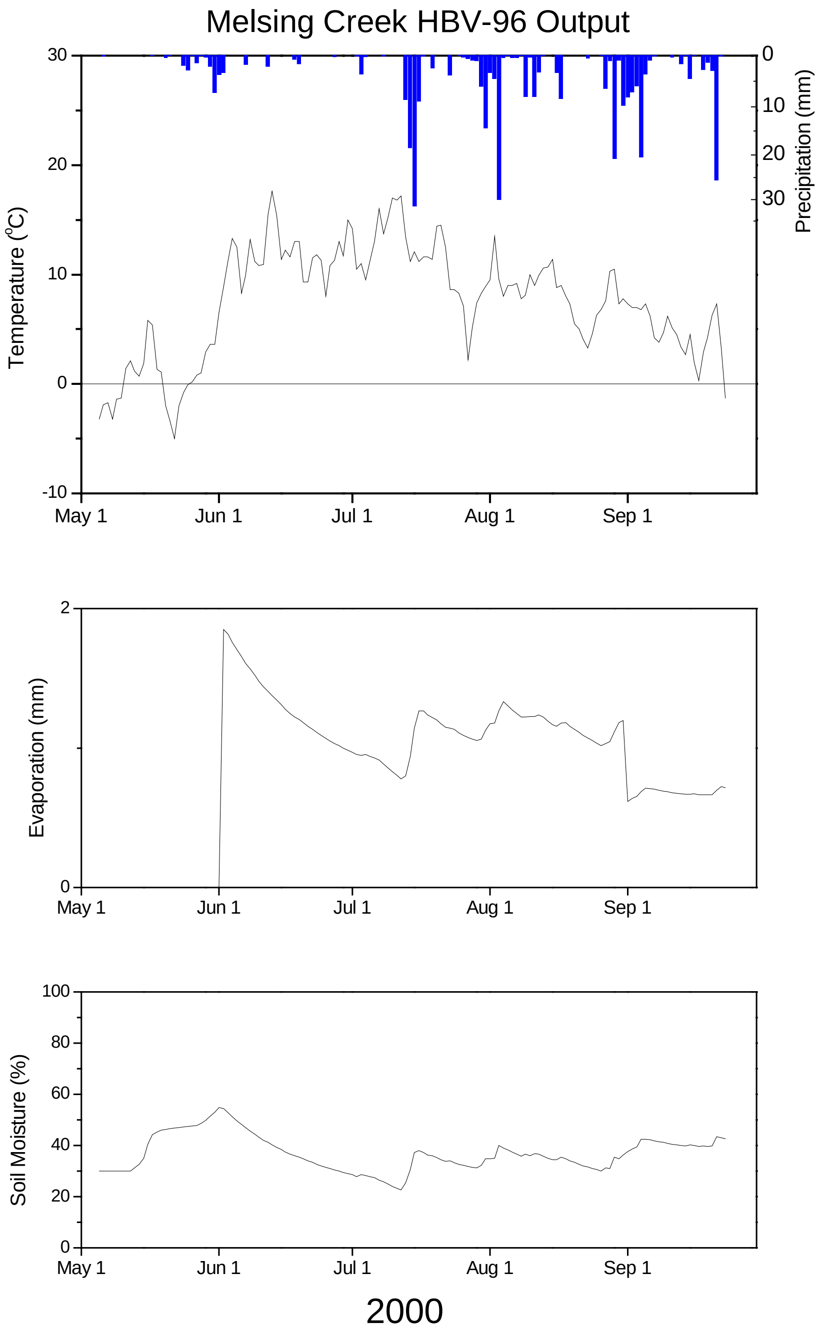

Figure 57. HBV-96 Model Output for Melsing Creek 2000.

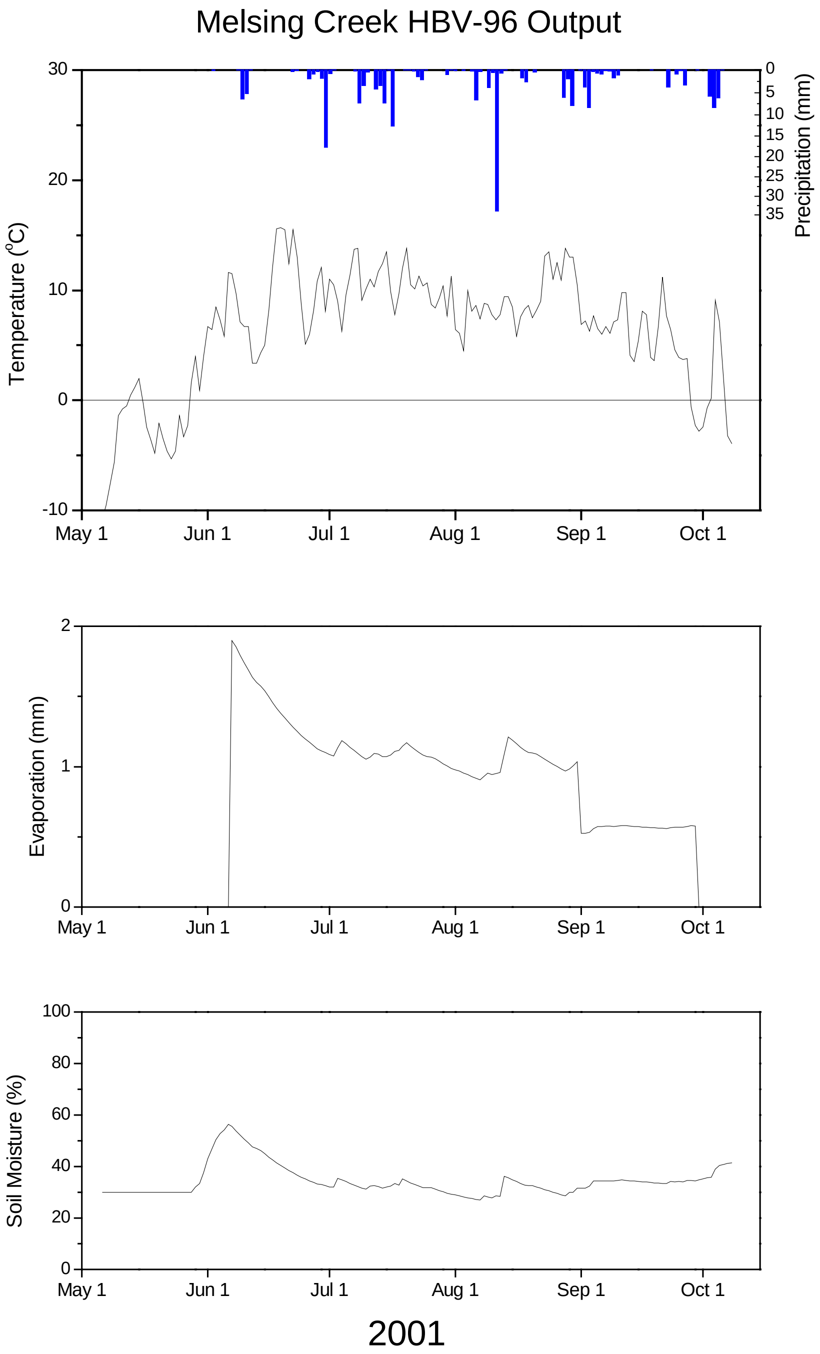

Figure 58. HBV-96 Model Output for Melsing Creek 2001.

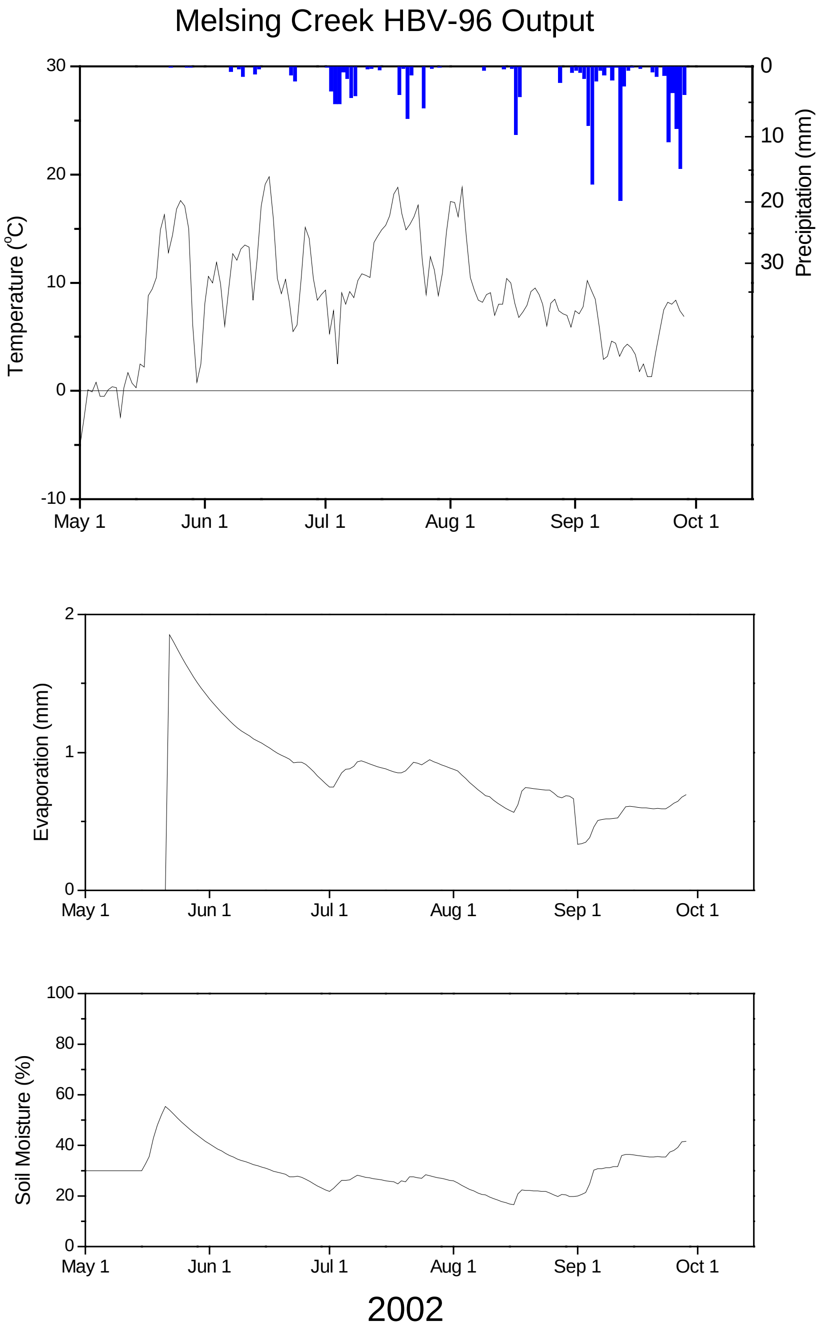

Figure 59. HBV-96 Model Output for Melsing Creek 2002.

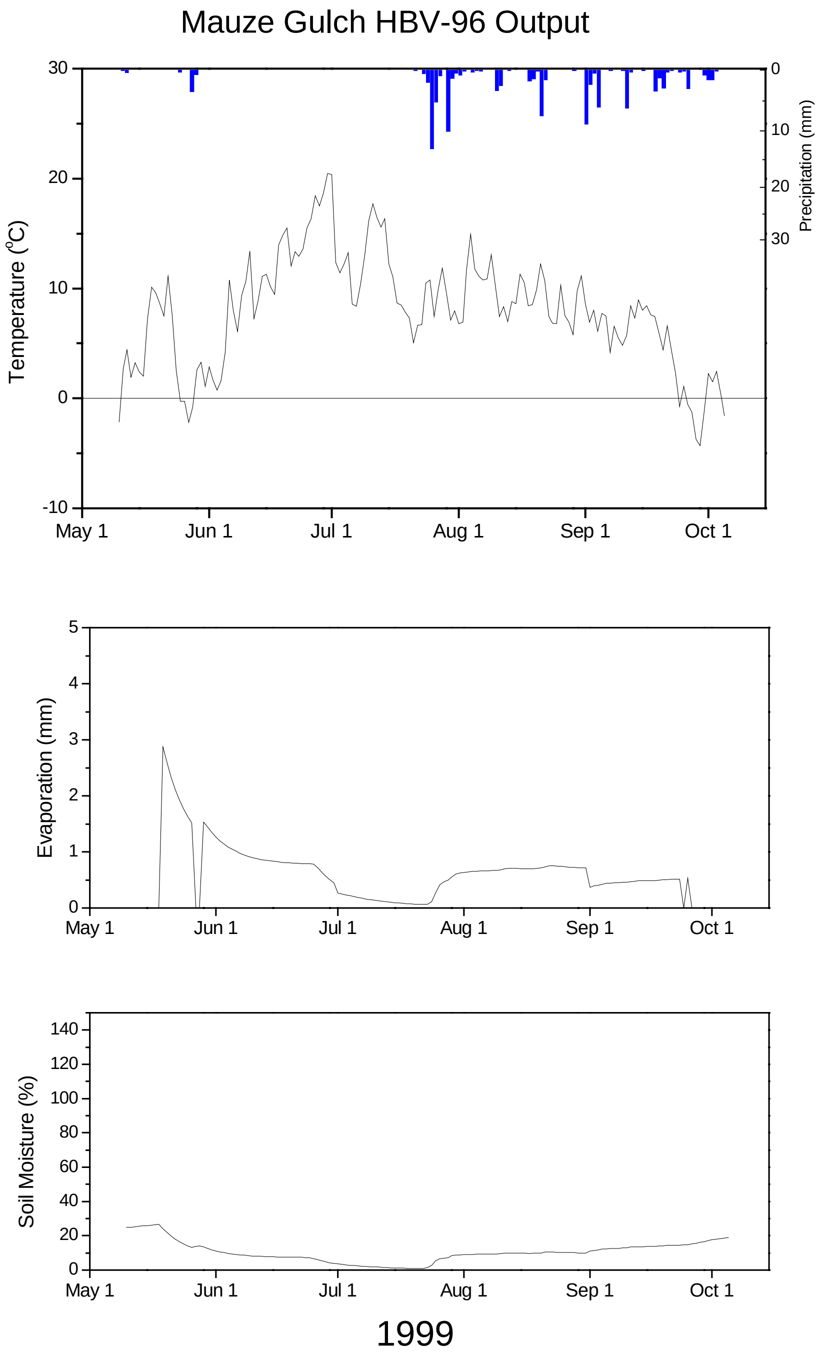

Figure 60. HBV-96 Model Output for Mauze Gulch 1999.

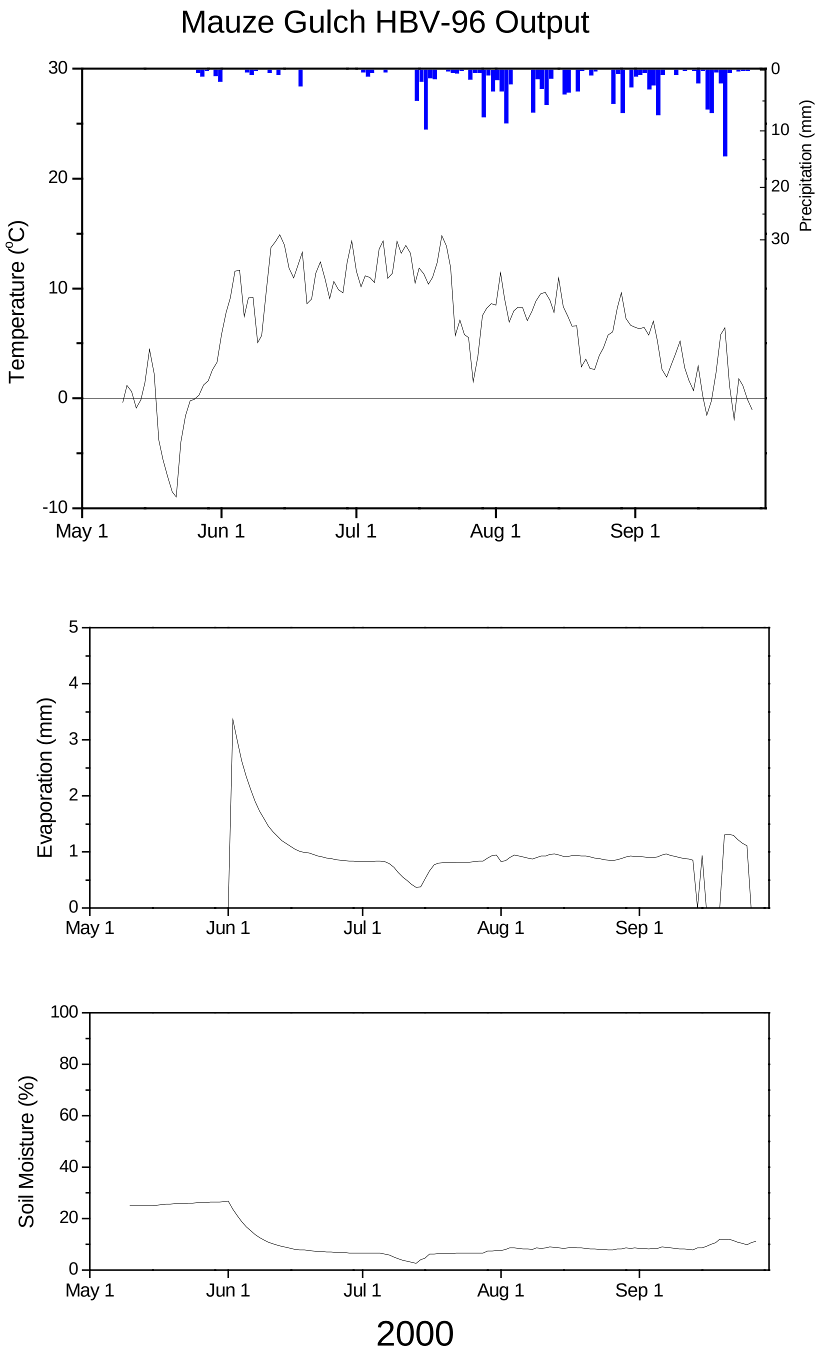

Figure 61. HBV-96 Model Output for Mauze Gulch 2000.

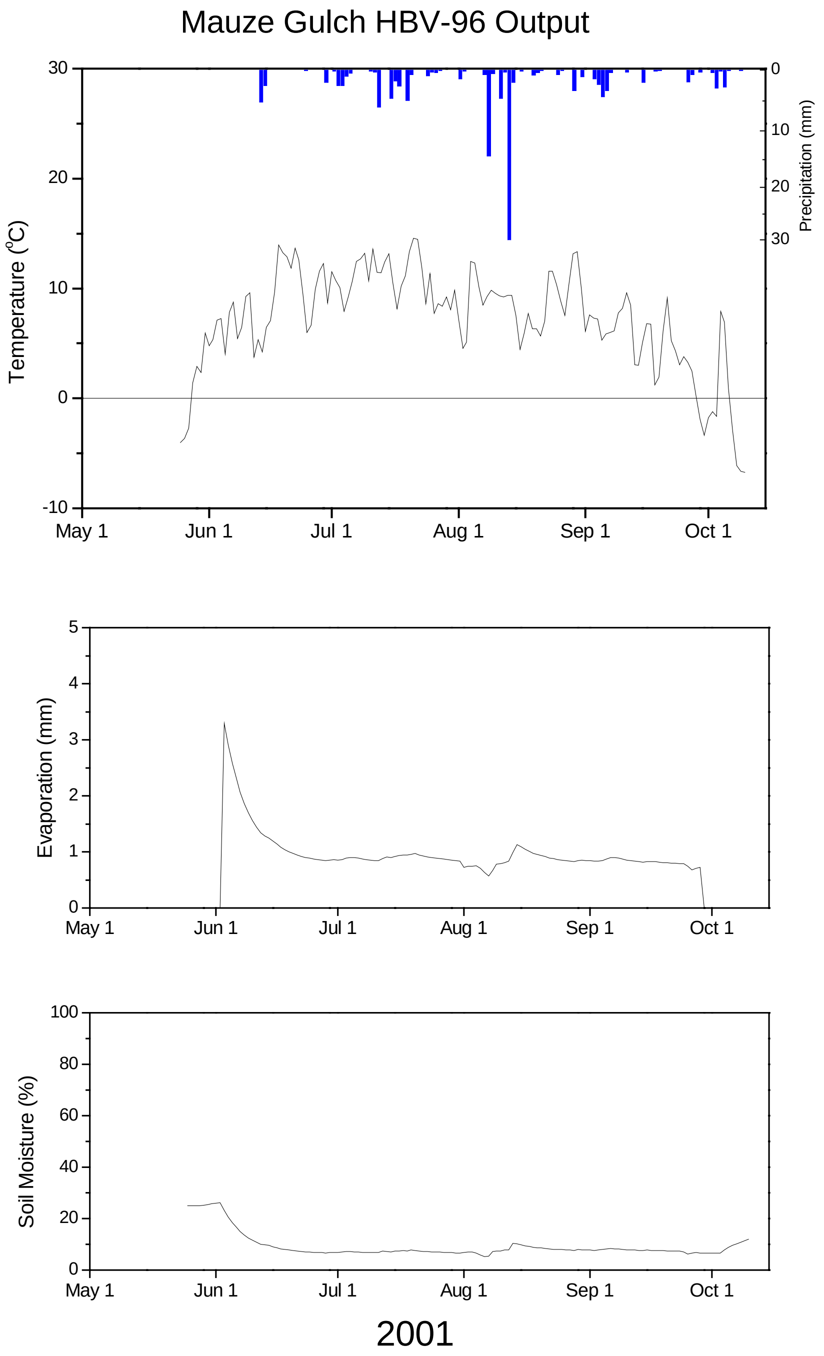

Figure 62. HBV-96 Model Output for Mauze Gulch 2001.

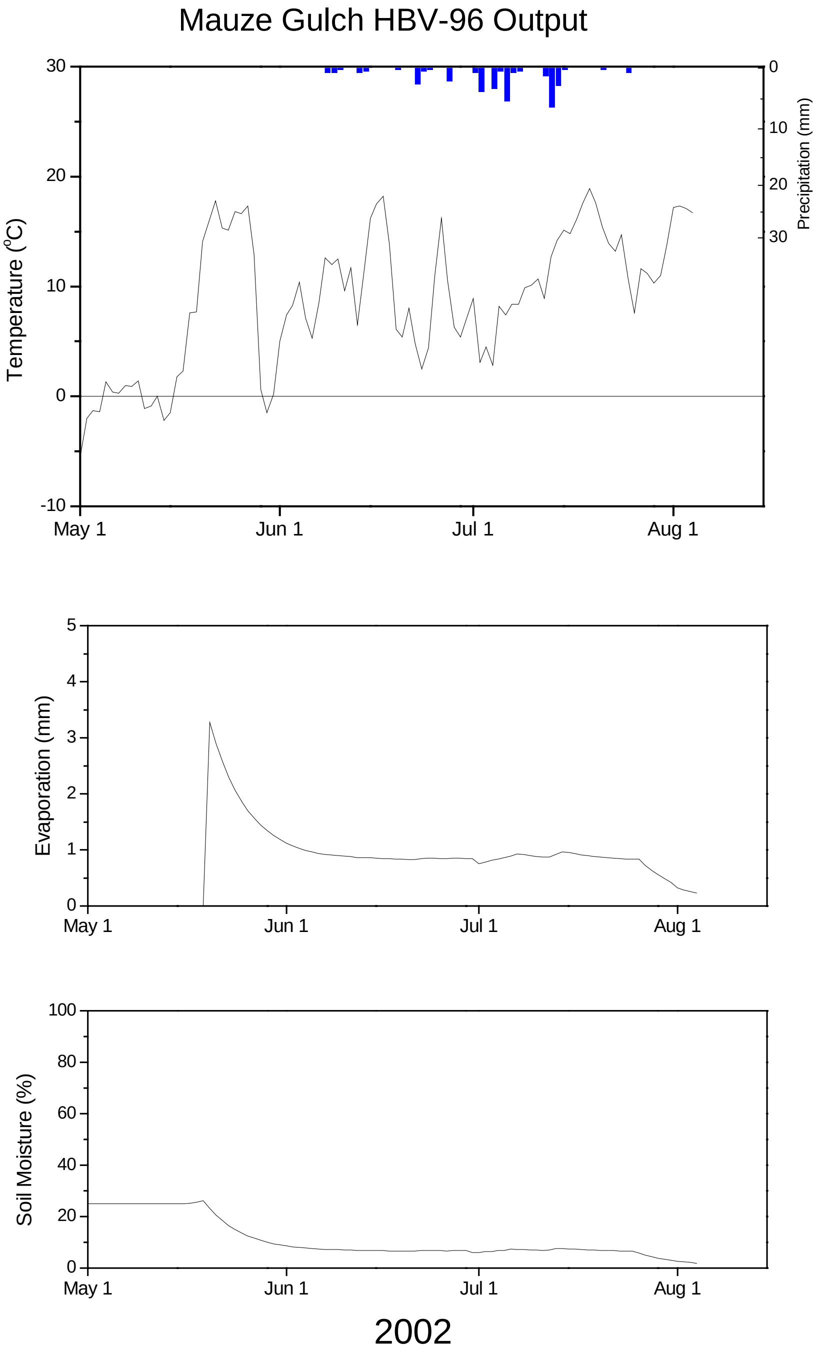

Figure 63. HBV-96 Model Output for Mauze Gulch 2002.

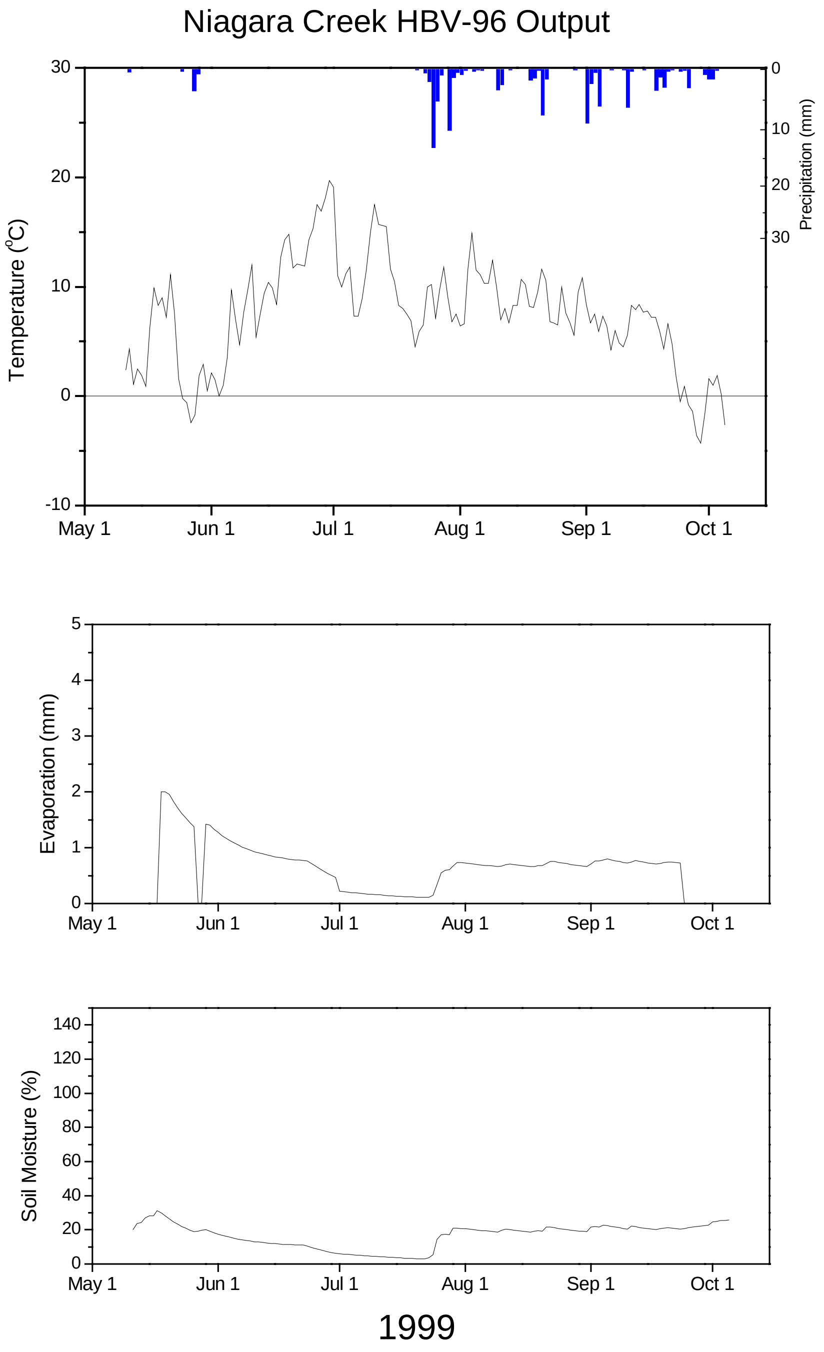

Figure 64. HBV-96 Model Output for Niagara Creek 1999.

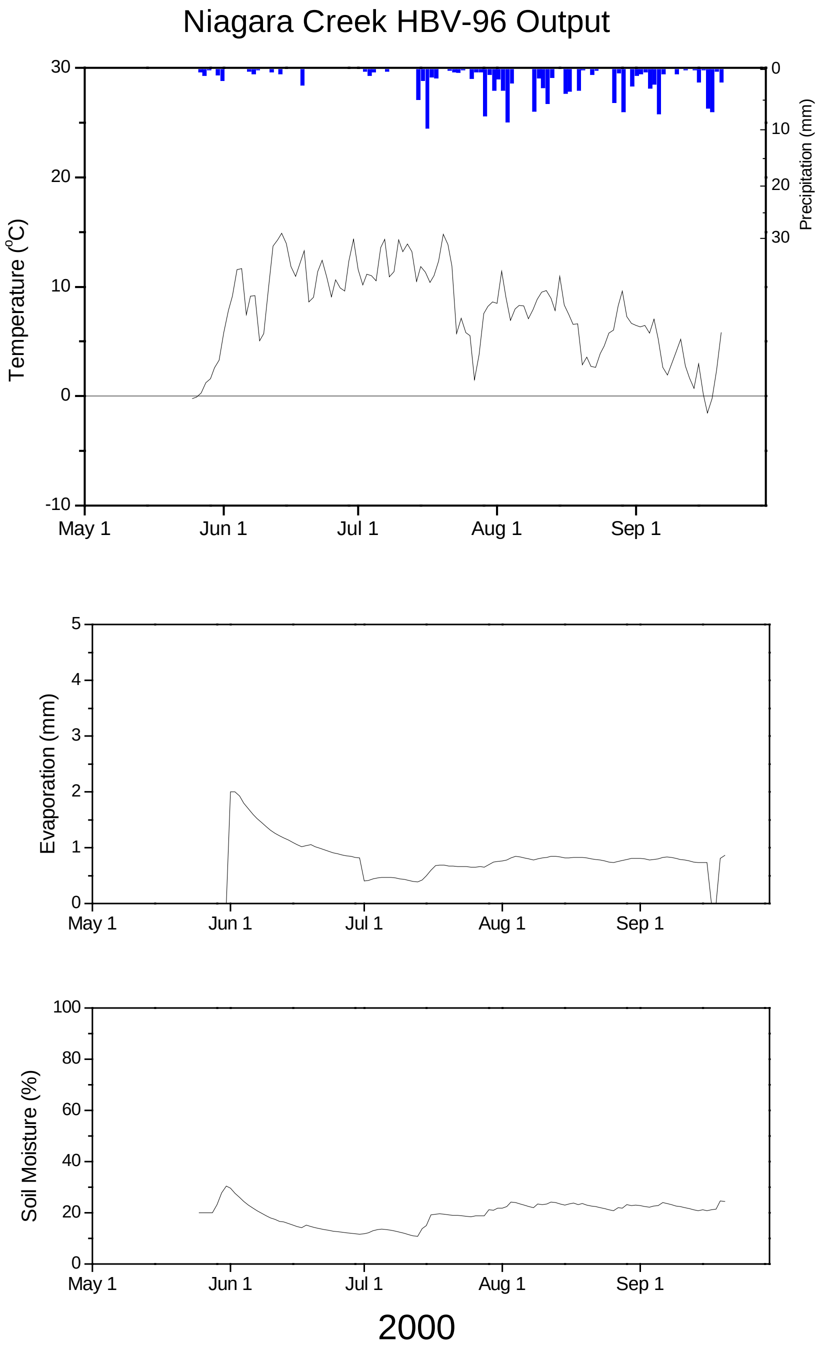

Figure 65. HBV-96 Model Output for Niagara Creek 2000.

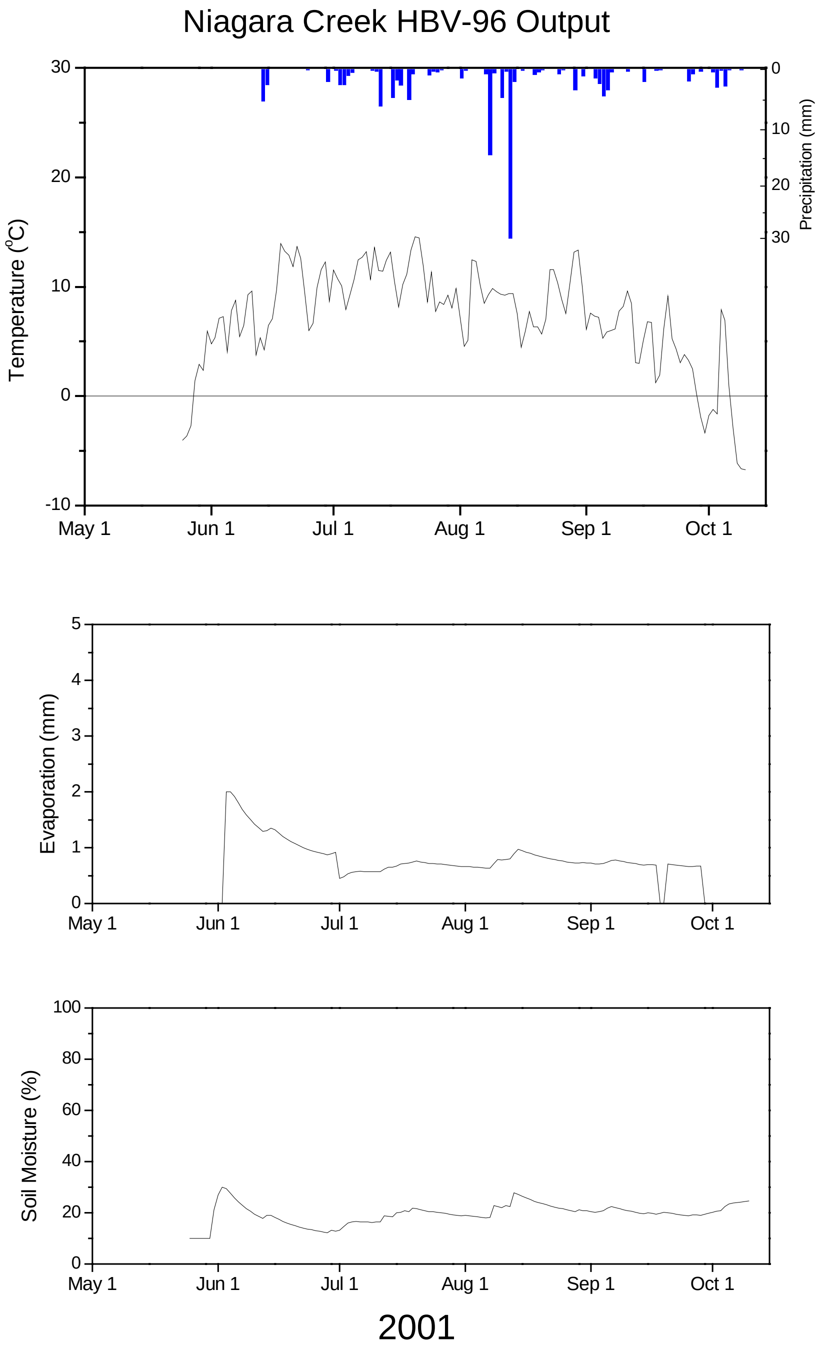

Figure 66. HBV-96 Model Output for Niagara Creek 2001.

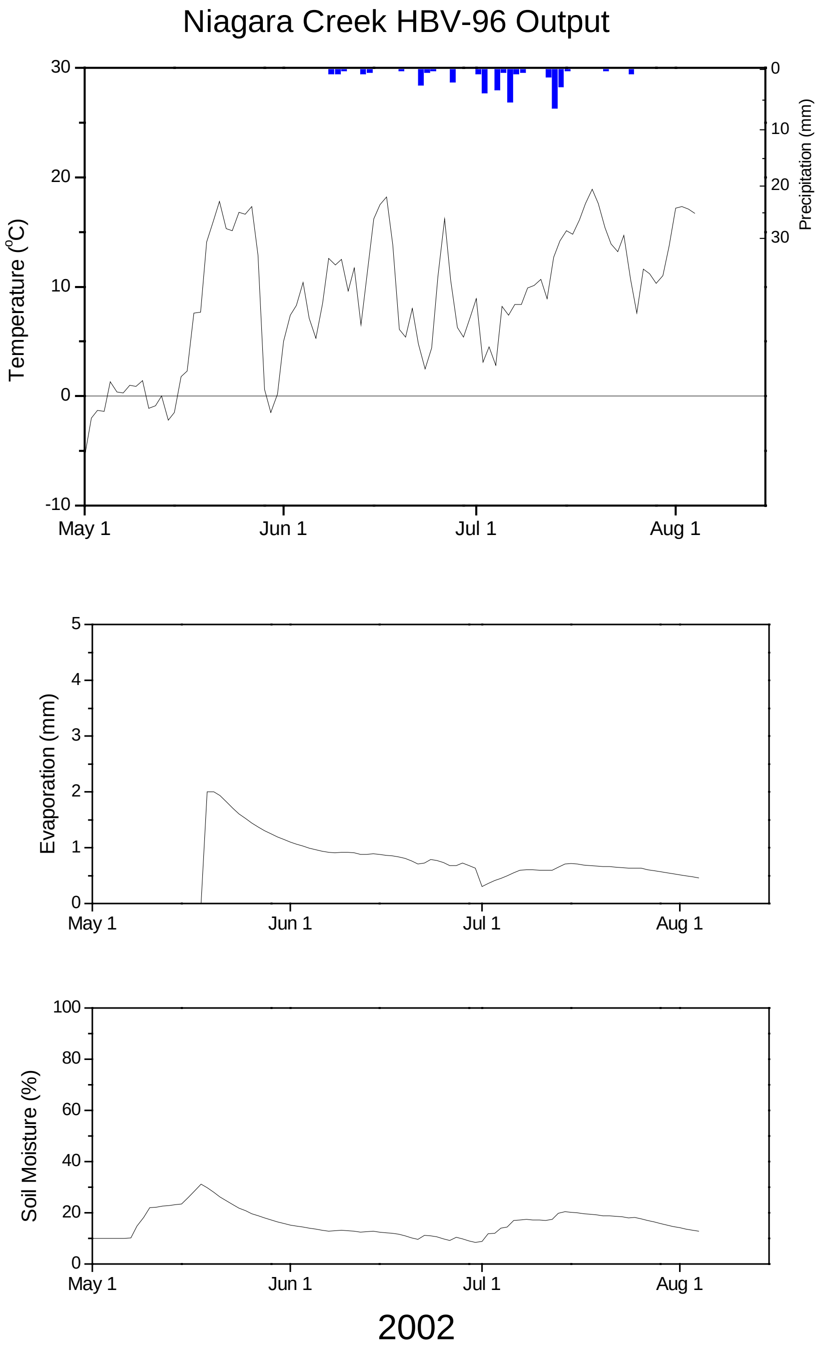

Figure 67. HBV-96 Model Output for Niagara Creek 2002.