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Derivation of Topoclimatic Indices for Alpine Snowpack Analysis in Alberta Rocky Mountain Watersheds

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ABSTRACT:

Mountains cover roughly one quarter of the Earth's land surface and have become known as the planet's water towers because they produce a surplus of water that is transported to neighbouring lowlands via alpine watersheds and vast river systems. The dominant source of water in the mountains is often snow, therefore, regional snowpack monitoring is important in hydrological studies and climate change. However, data used for these applications are often point-based and sparse, particularly in remote, inaccessible, rugged mountainous terrain where the hydrological and environmental gradients and variability are often the greatest. Therefore spatially explicit indicators over large areas are sought to augment detailed field investigations. In this paper, we present a series of high spatial resolution (25m) topographic and climatic (topoclimatic) indices derived for the Brown Creek Watershed in the Front Range of the Alberta Rocky Mountains as part of a broader study to support regional-scale snowpack and water availability estimates. Using geomorphometric derivatives from a digital elevation model (DEM) and topoclimatic factors derived from climate station and other data, a series of indices are presented that are related to precipitation, wind, snow, solar radiation, and temperature. These topoclimatic indices represent useful, first-order bulk estimates of individual key factors operating over different scales that collectively are related to major components of the hydrological cycle and the distribution of moisture in the region. This is a distinct improvement over simple interpolation of point-based field data owing to the incorporation of explicit spatial variability in spectral response, surface morphometry and terrain derivatives.

Keywords: water, precipitation, wind, snow, solar radiation, temperature, watersheds, topography, climate, mountains

1.0 INTRODUCTION

Source water from the Alberta Rocky Mountains drains to neighbouring prairie provinces in Canada, accounting for about 70% of the surface water supplies in the Prairie Ecozone. The dominant source of water in the mountains is often snow. Mountain snowpacks in western North America are a key component of the hydrologic cycle (Rood et al., 2005), storing water from the winter (when most precipitation usually falls) and releasing it in spring and early summer, when economic, environmental, and recreational demands for water throughout the west are frequently greatest (Mote et al., 2005). Thus, it is crucial to quantify the amount of water available from these areas as part of the hydrologic cycle. However, field studies to obtain these data can be challenging, costly and labour intensive given the vast, remote, inaccessible and rugged terrain that typifies mountain ecosystems. Furthermore, the large environmental and hydrological gradients in these areas dictate higher-density field sampling, yet the practical limitations in these large areas often result in low sample densities. Climatic variability in alpine environments of western North American is greater in the twentieth century, with ample evidence of increased winter and spring temperatures that has produced changes in both hydrology and plant communities (Mote et al., 2005). Future projections of broad-scale increases in temperature, along with uncertainties in regional variations of precipitation, suggest even further changes to hydro-climatic parameters over western Canada (Lapp et al., 2002; Bonsal et al., 2003).

The focus of this work, therefore, is on deriving spatially explicit information over large areas that is relevant for snowpack and water availability estimates in alpine ecosystems. In these areas, terrain variability is a major driver of hydrological processes, and therefore we have first derived topographic derivatives by geomorphometric processing of digital elevation model (DEM) data and have integrated these with point-based meteorological data to develop and adapt a series of topographic and climatic (topoclimatic) indices for hydrological applications. The resulting topoclimatic indices represent key hydrological factors that affect the moisture regime in Alberta Rocky mountains such as precipitation, wind, snow, solar radiation, and temperature. The derivation and hydrological significance of these indices is presented for an alpine watershed in the Front Range of the Alberta Rocky Mountains.

2.0 STUDY AREA AND GEOMORPHOMETRIC TERRAIN PROCESSING

2.1 Brown Creek Study Area

The Brown Creek Watershed (116°49'W, 51°43'N) is located within the Montane Cordillera Ecozone in the eastern slopes of the Front Range of the Alberta Rocky Mountains, approximately 90km southeast of the Jasper town site (Figure 1). The watershed is approximately 227km^2 and is found within the North Saskatchewan River Basin. Brown Creek is a tributary of the Brazeau River which flows into the North Saskatchewan River in west-central Alberta.

The surface geology in the Brown Creek watershed consists of two upper cretaceous formations: (1) the Alberta group (marine) consisting of shale and sandstone, and (2) the Brazeau (non-marine) formation comprising sandstone and shale. Thrust faulting is present within the watershed in a northwest trend (GSC, 1973).

Environment Canada 30 year normals from the nearby Nordegg meterological station (Figure 1) indicate that daily average temperature ranges between -11.27°C and 12.5°C, daily average rainfall ranges between 0.05mm and 102.8mm, and daily average snowfall ranges between 0cm and 28.2cm for the Brown Creek region.

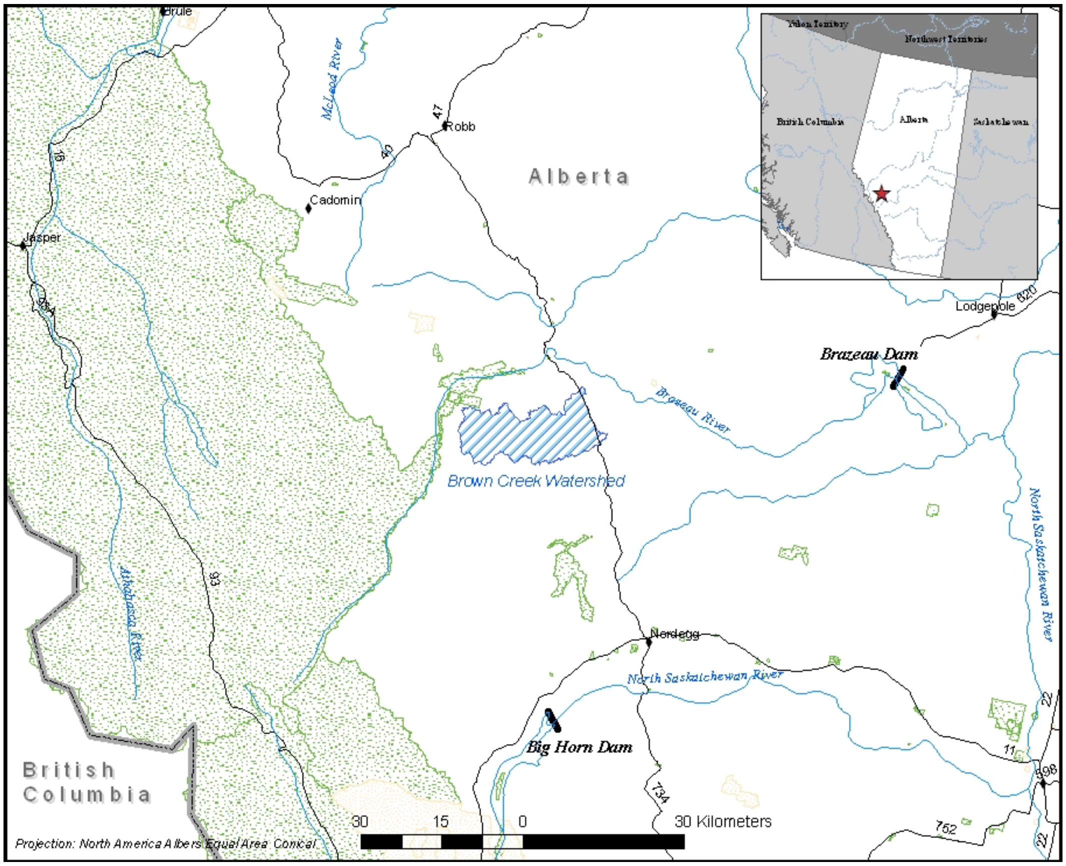

Figure 1: Brown Creek Watershed study area in west-central Alberta (inset map). Jasper and Banff National Parks shown in green. Continental Divide shown as gray line in lower left.

2.2 Topographic Data and Geomorphometric Processing

A 25m DEM for this site (Figure 2) was obtained from the Government of Alberta. This DEM was compiled as part of a provincial 1:60 000 aerial photography program which was completed in 1984 (Balce, 2003). Ground control points were collected during this time using an inertial survey system at a spacing of 20x10km by the Geodetic Survey of Canada and used for triangulation. Compilation of the 1:20 000 topographic maps was done using mainly stereoplotting (Balce, 2003). In 1997, the DEMs were processed and corrected using ArcInfo (see processing schematic Figure 3). The DEMs were then checked for accuracy using a helicopter-borne laser profiler and were deemed to have a vertical accuracy of 3.05m (Balce, 1987).

The DEM obtained for this project was post-processed to remove erroneous pits and artifacts due to resampling and interpolation. Although some depressions may not be spurious, this provided a terrain surface suitable for hydrologiocal GIS applications such as streamflow determination and watershed modeling (Doan, 2000). As the DEM had the coarsest spatial resolution of the various spatial data sets in this study, all other raster data were transformed to this (25m) resolution.

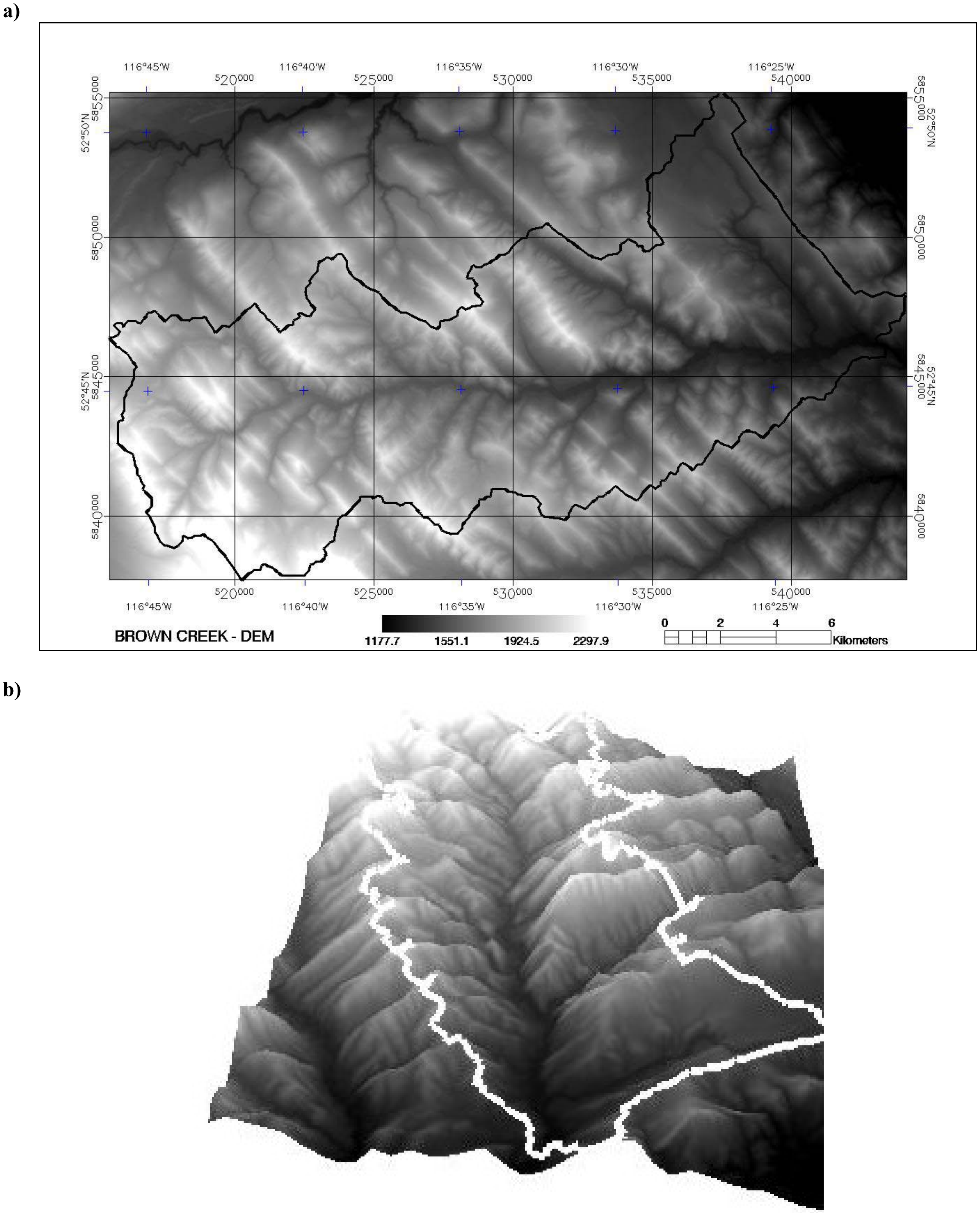

Figure 2: Digital elevation model (DEM) of Brown Creek watershed, spatial resolution=25m: a) plan view, north to top, watershed boundary in black; b) 3-D perspective view looking west; vertical exaggeration applied, watershed boundary in white.

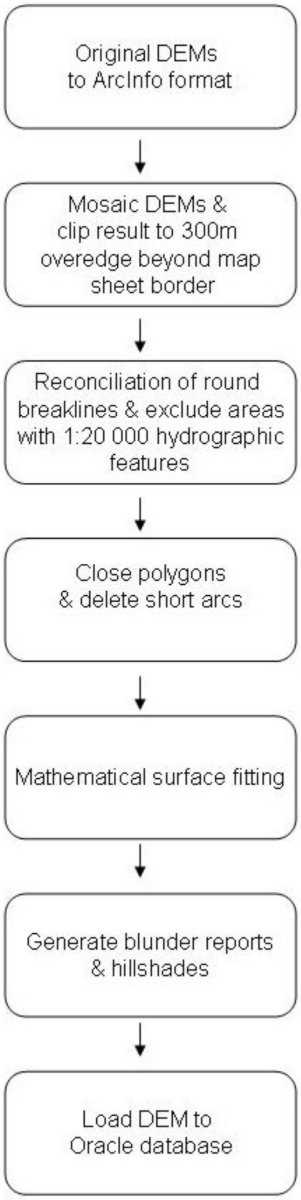

Figure 3: Processing schematic adapted from Balce (2003).

As a result of the importance of topography in modifying the effects of climatic factors and for influencing alpine moisture regimes and the availability of water, a set of first and second-order terrain surface descriptors was derived from the DEM according to the general system of geomorphometry (Evans, 1972; Peddle and Franklin, 1990; Duke et al., 2003) using the ENVI topographic modeling system (ENVI, 2005). Using a 3 x 3 kernel, a quadratic surface was fitted to the DEM, from which slope (Figure 4) was derived as the rate of change of elevation (first vertical derivative), as well as aspect (Figure 5), the direction terrain faces (first horizontal derivative of elevation). Higher-order derivatives of longitudinal (down slope) profile convexity and cross sectional plan (cross slope) convexity were also computed for future use (ENVI, 2005).

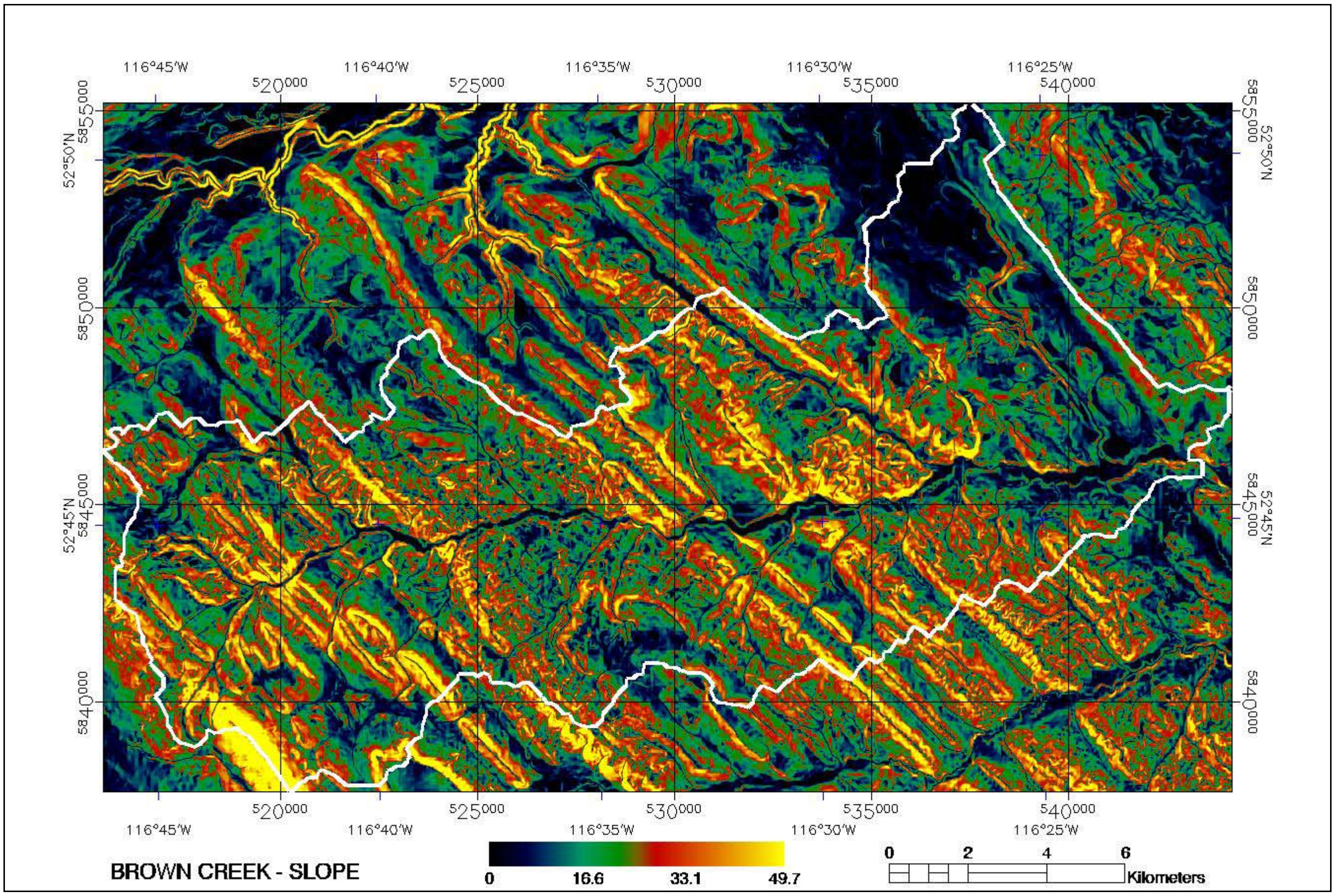

Figure 4: Slope image of Brown Creek watershed (white polygon) computed from DEM as first vertical derivative of elevation.

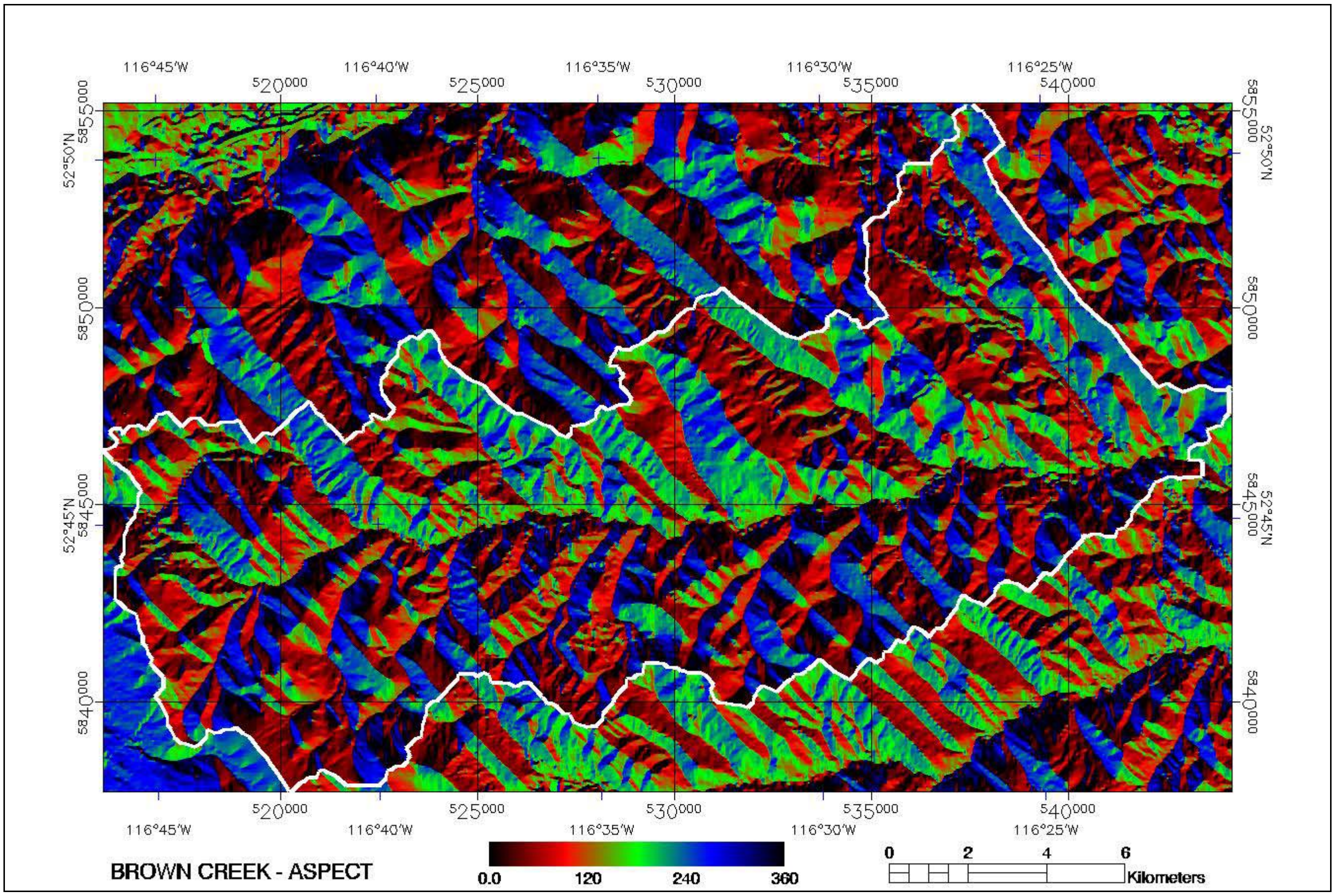

Figure 5: Aspect image of Brown Creek watershed (white polygon) computed from DEM as first horizontal derivative of elevation. Note that colour gradation is similar for orientations at and near due north (e.g. 0 and 360º).

3.0 TOPOCLIMATIC INDICES FOR HYDROLOGICAL APPLICATIONS

The focus of this component of our research is on determining suitable variables which may capture significant information pertaining to precipitation, temperature, wind, and radiation. These parameters contribute to complex interactions among physical processes which control moisture regimes in alpine watersheds and could potentially be used as input to micro-scale hydrological models (watershed level). These scaled-outputs, or the topoclimatic indices themselves, may also be useful to parameterize larger, regional-scale hydrological models (basin level or larger). We have developed customized software to process the available topographic, spectral and meteorological data into the following topoclimatic indices (hydrological parameter shown in brackets):

(i) Orogenic Precipitation Index (precipitation);
(ii) Slope-Aspect Index (wind: snow redistribution);
(iii) Snow Melt Degree Days Index (temperature, snow melt); and
(iv) Insolation Index (solar radiation).

These topoclimatic indices are intended to provide first-order estimates of individual components that affect the hydrological cycle in high relief, alpine watersheds, and follow from earlier work by Peddle and Duguay (1995) that developed topoclimatic indices for an ecological study of alpine tundra vegetation in the Colorado Rockies. We emphasize that in adapting these for use in a hydrological context, the topoclimatic indices derived here are intended as first-order, bulk estimates of important hydrological phenomena. They inherently cannot provide the level of information possible from field measurement, but instead provide a mechanism to extend and distribute that information content throughout an area. An important point, however, is that we are not performing simple spatial interpolation of point-based field data but instead have developed a considerably more sophisticated approach using direct spatial data that captures variability across landscapes and watersheds as a function of satellite image spectral response and topographic derivatives, and which links to field measurement. The development and physical significance of each of these indices for watershed applications in Alberta are discussed next, together with maps of each index derived for the Brown Creek watershed.

3.1 Orogenic Precipitation Index

Precipitation in Alberta is significantly influenced by the Rocky Mountains, particularly on the east slopes of the Front Range where source water is distributed to lower elevations on the Prairies. Precipitation is affected by both altitude and distance from the Continental Divide in Front Range environments (Ives and Dow, 1982), resulting in a precipitation gradient and spatial-topographic influences on alpine moisture regimes and consequently water availability. The Orogenic Precipitation Index (OPI) defined by Peddle and Duguay (1995) in Colorado has been adapted for this hydrological application in the Alberta Rockies as a function of elevation and grid (pixel) distance from the Continental Divide. Precipitation increases both with altitude (Ives and Dow, 1982) and with proximity to the Continental Divide (Komárková and Webber 1978), thus the Orogenic Precipitation Index (OPI) was defined as:

$$OPI = \frac{a}{dcd}$$

where: a = altitude

dcd = distance to the Continental Divide

which we interpret with respect to precipitation in this Front Range region. Higher OPI values represent a greater likelihood for higher relative precipitation amounts and, consequently, greater moisture availability. Other factors that influence site-specific moisture availability are extracted from other indices and data sources. As mentioned previously, a given topoclimatic index such as OPI is intended to provide information on one component of the hydrological cycle, namely the original supply and likelihood of incident precipitation, but without reference to other factors such as snow redistribution, melt or water run off. Specific conditions with respect to location or time (e.g. weather) are also not considered in the OPI. These factors are controlled by other hydrological processes that have been incorporated in some of the other topoclimatic indices that use point-based meteorological station data (e.g. SMDDI) or which could be addressed using observed data in higher level hydrological models. However, when used together, the integrated set of topoclimatic indices should collectively provide broader, more comprehensive information on site-specific water availability.

At each pixel location in the Brown Creek watershed, elevation was obtained directly from the DEM, with distance to the Continental Divide (CD) determined from GIS overlay analysis of the CD feature and derivation of the number of pixels as an offset from the current location to the CD, and then employing the pixel dimensions (25m DEM) to derive the actual distance. The OPI map derived for Brown Creek watershed is shown in Figure 6. The highest values, as expected, are located in the western-most portion of the watershed that are at higher elevations and closer to the CD, however there are also smaller but likely significant areas of similarly high OPI values east of there, as found along both the northern and southern boundaries of the watershed and ranging to the approximate midpoint along the east-west axis of the watershed. Mid-range to lower values of OPI are found primarily in the eastern portion of the watershed, with the lowest values in the north-east and in the eastern extent of the valley of Brown Creek along the east-central part of the area. These collectively provide a broad characterization of potential moisture availability through incident precipitation.

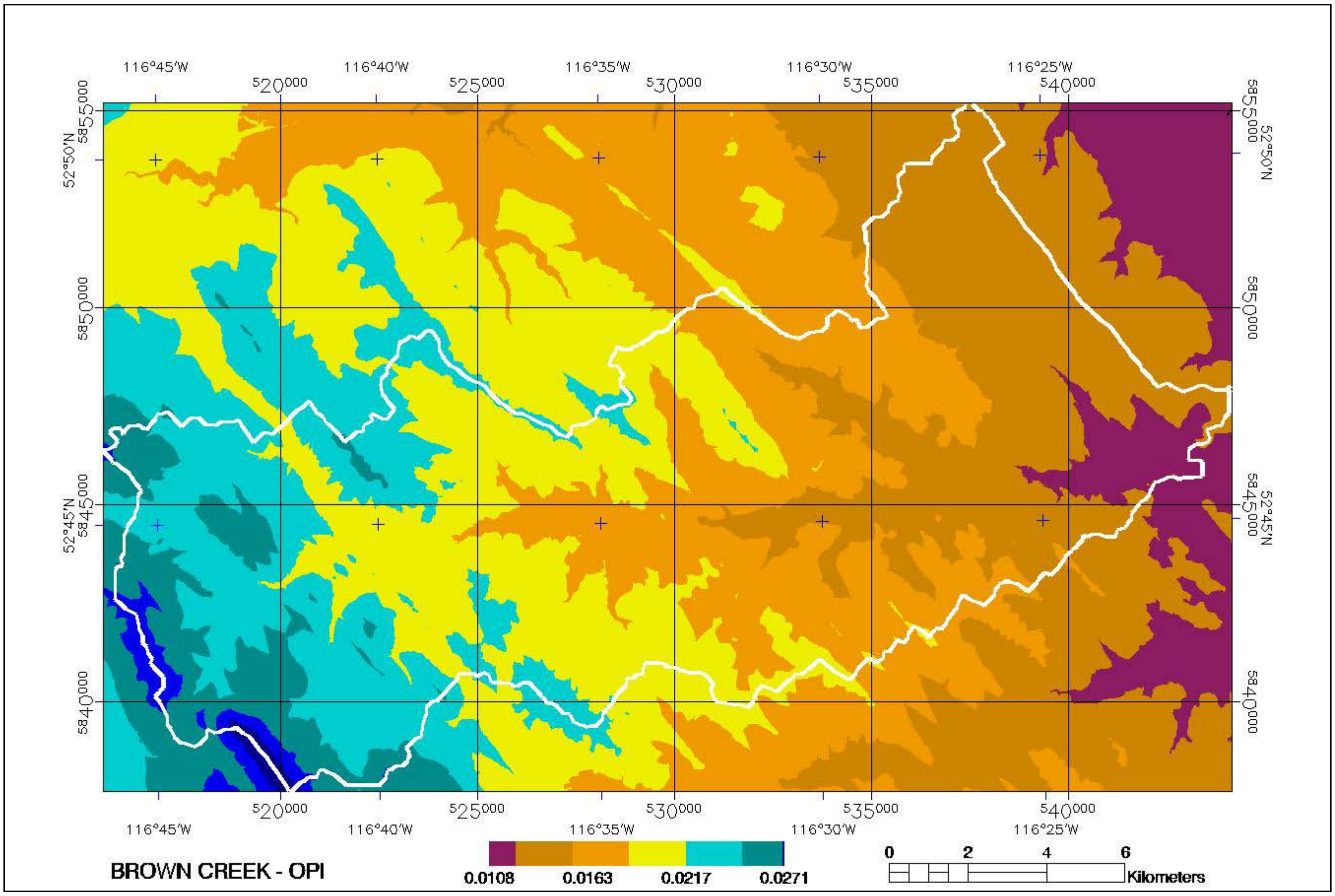

Figure 6: Orogenic Precipitation Index (OPI) map of Brown Creek watershed (white polygon) computed as DEM altitude divided by distance to Continental Divide (west of watershed).

3.2 Slope-Aspect Index

Wind is a significant factor in the redistribution of freshly fallen snow (Essery and Pomeroy, 2004) in Front Range environments such as the Brown Creek watershed. Strong prevailing westerly winds create deep, long lasting snow fields on leeward (east-facing) slopes while windward (west-facing) slopes are left virtually snow free, unless modified by factors such as surface roughness or vegetation density. The resulting distribution of snow affects the dynamics, timing and magnitude of snow ablation owing to the distribution of deeper snow fields in some areas, while other areas have minimal snow cover or are snow-free. This in turn affects the availability of water for hydrological and ecological processes.

The topoclimatic Slope Aspect Index (Frank 1988) utilizes first-order surface geomorphometry to establish terrain orientations likely to contain more moisture from snow redistribution (high values of SAI), and those expected to be exposed, windblown, and dry with low moisture availability (low SAI). SAI values were computed with respect to terrain slope and surface aspect as it relates to wind direction (west prevailing) using the equation (Frank, 1988):

$$SAI = \sin(s) * asw$$

where s is terrain slope, and asw is the angular separation of terrain aspect from due west.

SAI values for Brown Creek watershed are shown in Figure 7. Unlike OPI, there is considerable local variability in SAI throughout the watershed in that for most areas both high and low values are found. This is driven by the topography of the watershed in which there is an extensive network of secondary streams and tributaries (Figure 2) in valleys that run generally perpendicular to and drain into the east flowing Brown Creek (Figure 2). These secondary valleys exist throughout most of the watershed and have a high occurrence of both east and west-facing slopes, thus leading to a complex of snow redistribution features and the SAI values derived. Although additional local variation is provided by slope, the primary factor determining SAI variability in this watershed is aspect (Figures 4 and 5). The highest SAI values are found on steep, leeward (east facing) slopes where snow accumulation is great and moisture is readily available, whereas windward, exposed, desiccated areas that are likely to remain snow free are characterized by low SAI values. When considered with OPI, the SAI values provide a more local-scale indicator of snow redistribution whereas OPI provides a more regional scale, first-order estimate of moisture supply. Both scales are important in developing an improved understanding and characterization of the hydrology of the area.

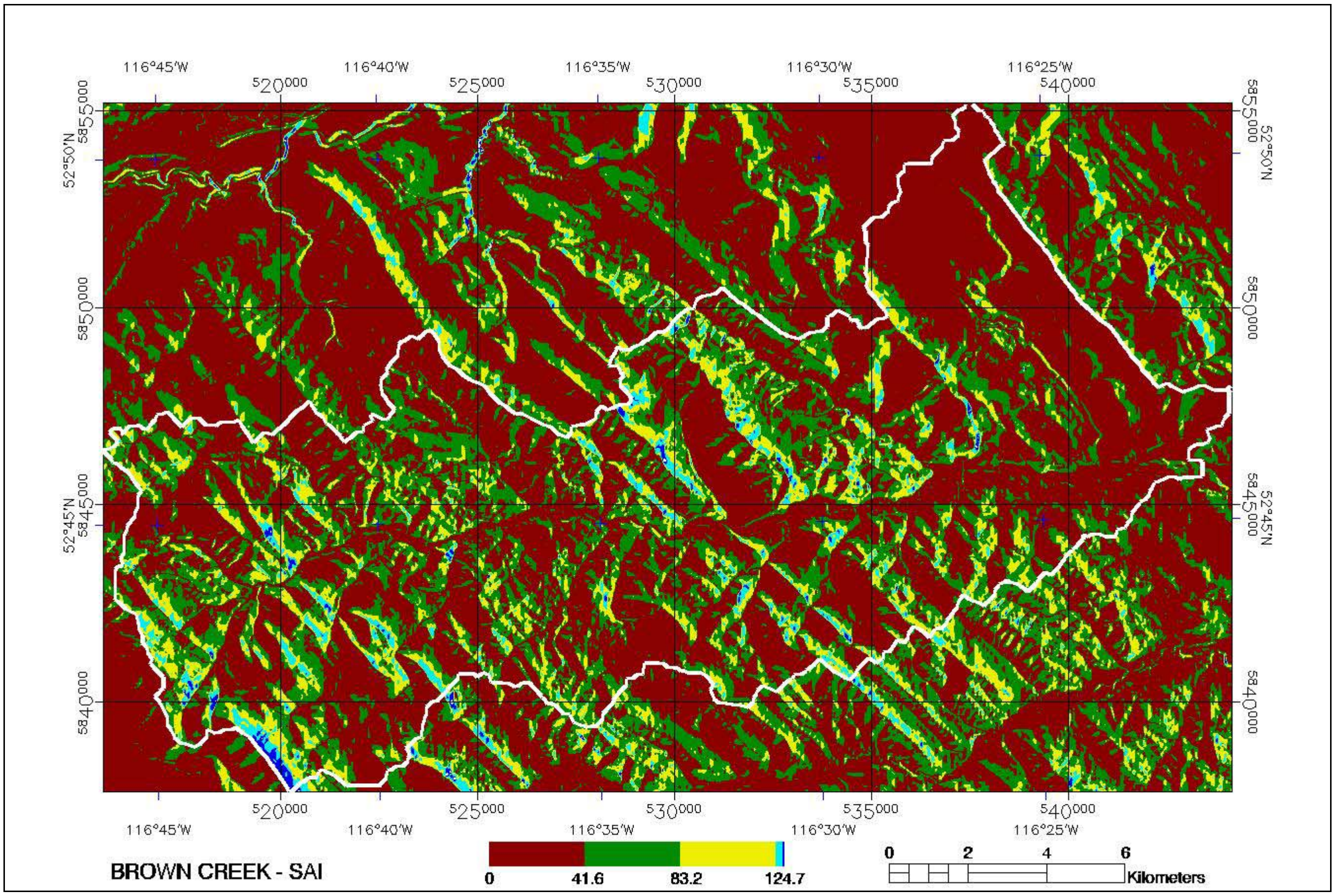

Figure 7: Slope-Aspect Index (SAI) map of Brown Creek watershed (white polygon).

3.3 Snow Melt Degree Days Index

Temperature is a primary factor controlling the initiation and rate of snow melt. Over a watershed, it is useful to estimate the cumulative amount of energy available for snow melt throughout the primary snow melt period in the spring time. Snow Melt Degree Days (SMDD) refers to the magnitude a given temperature measure exceeds a standard level at which snowmelt is initiated. For alpine environments, 0˚C is generally considered to be the standard threshold above which snowmelt will occur. So, for example, an average temperature of 5˚C on a given day would correspond to 5 snow melt degree days, whereas a daily average temperature of 0˚C (or lower) would have a SMDD value = 0, indicating no potential for snow melt based on temperature. More specific implementations can involve diurnal temperatures or daily highs, however, for broad area studies such as this the daily average is a sufficient indicator.

In this study, we calculated SMDD cumulative totals throughout the Brown Creek watershed during the primary snow melt and spring runoff period using daily mean temperatures obtained from point-based meteorological station data. These data were extended throughout the watershed as a function of environmental temperature lapse rates applied to pixel-specific DEM data. Using software developed in-house, estimates of temperature were derived at each pixel in the study site for each day throughout the period of interest. This was achieved based on average daily temperature derived from readings obtained at the Environment Canada Nordegg meteorological station (elevation 1320 m a.s.l., 35 km southeast of the watershed – see Figure 1). Average daily temperature was calculated using a cosine function applied to minimum and maximum temperature readings (Johnson, 1983). Using these measurements from the Nordegg met station as a benchmark, we applied known environmental temperature lapse rates for Brown Creek (Shea et al., 2004) for each month/season which define the inverse relationship between temperature and altitude. Using these lapse rates, temperature at each pixel in the watershed was estimated as a function of altitude information extracted directly from the digital elevation model to obtain daily temperature grids throughout the snow melt period. Once the daily temperature grids were computed, the final step was to obtain the cumulative daily SMDD totals using a simple GIS overlay function to derive the sum of daily SMDD results from each daily temperature grid coverage at each pixel, with the resulting map shown in Figure 8.

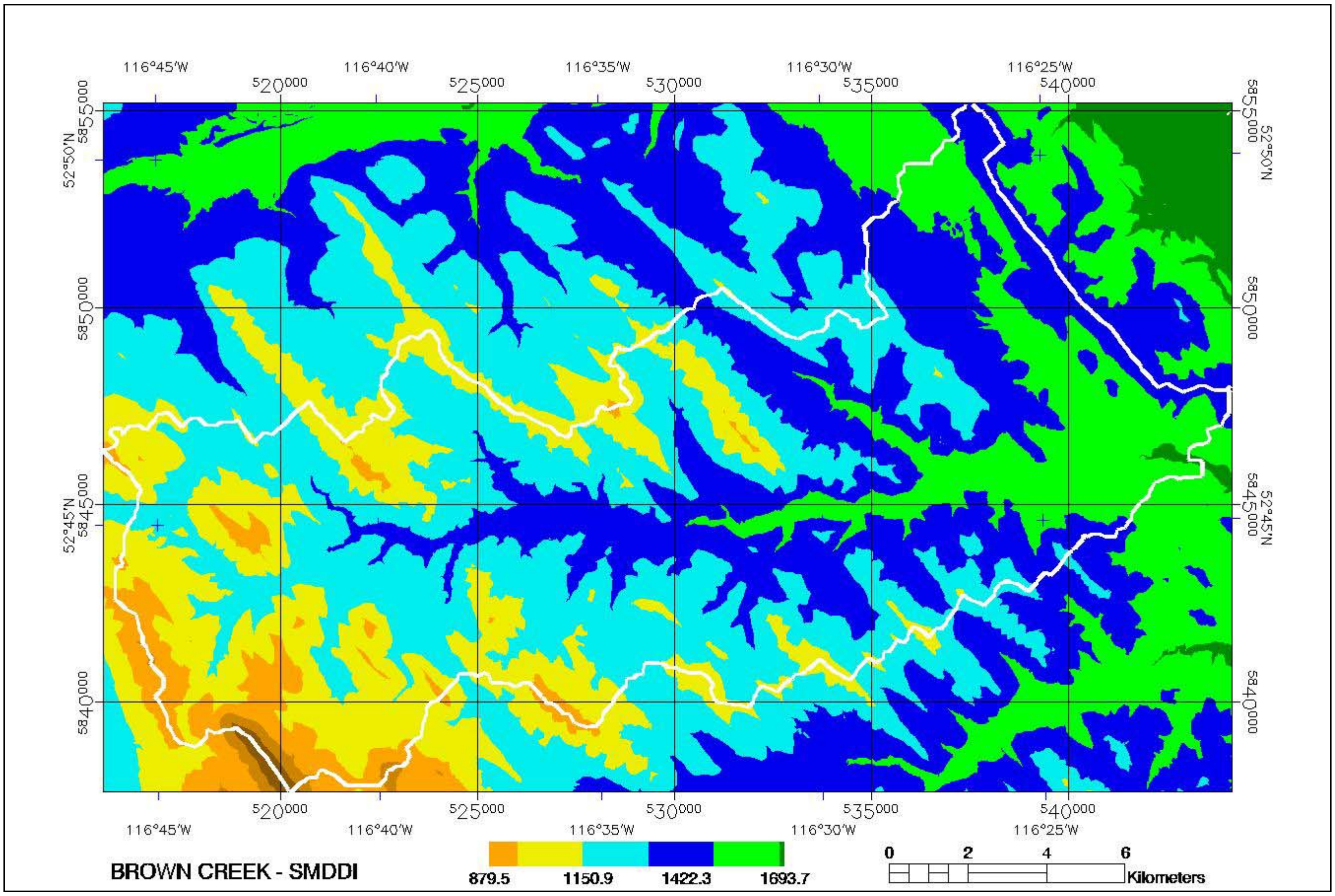

Figure 8: Snow Melt Degree Day Index (SMDDI) map of Brown Creek watershed (white polygon).

The SMDDI map for Brown Creek shows a trend of decreasing cumulative SMMD with altitude, as expected, with lower values found primarily in the eastern portion of the watershed, and high values to the west. However, an interesting feature of this map is the presence of low SMMD values along the northern and southern margins of the watershed associated with higher elevations that exist upslope from several tributaries that feed into Brown Creek. In these areas, there is a steep gradient of snow melt potential, as indicated in Figure 8 by the bands of low SMMD values (yellow) towards the eastern (right) portion of the watershed that are in relatively close proximity to some of the highest (green) SMMD values. Similar gradients exist further up the valley where low to moderate SMMD values are within several kilometres of some of the highest SMMD values obtained in the watershed. This may suggest a more variable dynamic in the timing of snowmelt onset and rate within smaller regions, which could influence water runoff rates from these areas compared to similar size areas that have a much lower range of SMMD, for which most primary runoff may occur within a more compressed time period. Testing this assertion, which in the field would ideally include accounting for other factors that influence snow melt, is beyond the scope of the present study. We conclude, however, that SMMDI provides useful information on the spatial distribution of snow melt potential throughout the watershed.

3.4 Insolation Index

Solar insolation is the primary driver in a number of ecological and hydrological processes including snow melt, surface water evaporation, and soil moisture (Kang et al., 2002; Pomeroy et al., 1998; Dubayah and Loechel, 1997, Olyphant, 1984). Insolation refers to the magnitude of interception of solar shortwave energy by an exposed surface (Strahler and Strahler, 1987). In this study, the Solar Analyst software (Fu and Rich, 1999; HEMI, 2000) was used to compute direct, diffuse, and global insolation for each DEM pixel within the Brown Creek watershed for typical seasonal days (i.e. spring, summer) using hemispherical sunmaps, skymaps, and visible skymaps produced for each pixel using ArcGIS software. Direct insolation (Dir_{tot}) is a function of solar flux at the top of the atmosphere (S_{const}), atmospheric transmittivity (τ), relative optical pathlength as a function of the solar zenith angle ($m(\theta)$), duration of solar incidence ($SunDur_{\theta,\alpha}$) for a given solar zenith (θ) and azimuth angle (α) calculated for each skymap sector, sky not obscured by terrain for the sunmap sector ($SunGap_{\theta,\alpha}$), and the angle of incidence ($Inc_{\theta,\alpha}$) calculated using solar geometry, terrain slope (T_{slope}) and aspect (T_{aspect}), as:

$$Dir_{tot} = \sum Dir_{\theta,\alpha} = S_{const} \cdot \tau^{m(\theta)} \cdot SunDur_{\theta,\alpha} \cdot SunGap_{\theta,\alpha} \cdot \cos(Inc_{\theta,\alpha})$$

where:

$$Inc_{\theta,\alpha} = \mathrm{acos}(\cos(\theta) \cdot \cos(T_{slope}) + \sin(\theta) \cdot \sin(T_{slope}) \cdot \cos(\alpha - T_{aspect}))$$

Diffuse insolation is calculated using a uniform diffuse model (Fu and Rich, 1999). For each sky sector, diffuse insolation is calculated as:

$$Dif_{tot} = \sum Dif_{\theta,\alpha} = R_{glb} \cdot P_{dif} \cdot Dur \cdot SkyGap_{\theta,\alpha} \cdot W_{\theta,\alpha} \cdot Inc_{\theta,\alpha}$$

where R_{glb} is the global normal radiation calculated as:

$$R_{glb} = (S_{const} \cdot \sum \tau^{m(\theta)}) / (1 - P_{dif})$$

$W_{\theta,\alpha}$ is a diffuse radiation weighting factor for a given sky sector, P_{dif} is the proportion of diffuse global normal radiation flux, $SkyGap_{\theta,\alpha}$ is the gap fraction for a given sky sector, and Dur is the time interval for analysis. Global insolation (G_{tot}) is calculated as the sum of the direct and diffuse components:

$$G_{tot} = Dir_{tot} + Dif_{tot}$$

The surface incidence angle and proportion of unobscured hemisphere for a given grid cell is of particular importance in alpine/sub-alpine watersheds as they have a significant effect on instantaneous insolation received in rugged terrain as well as duration of direct insolation.

The instantaneous direct and diffuse insolation (Figure 9 and 10) components for each grid cell were combined with the duration of direct insolation (Figure 11) to create the insolation index (INI) for Brown Creek watershed (Figure 12). INI equates to the amount of radiative energy received across all wavelengths over the course of a typical seasonal day. The INI map shows considerable local variation in insolation throughout the Brown Creek Watershed, with no distinct area having significantly greater or lower overall totals, with the exception of the extreme north-eastern part of the watershed where insolation totals are generally moderate to low. Areas of highest insolation are related primarily to those portions that receive greater direct beam radiation, which is significant given the greater influence this has on increased snow melt rate. Areas of low direct and diffuse radiation and duration, as seen also in the INI map (Figure 9), are also important since snow in these areas may have a greater likelihood of becoming longer lasting snowfields, provided sufficient snow depth and other factors are consistent for preservation. In these instances, the rate of snow melt and possibly runoff will be lower during any given period (between precipitation events), and likely more consistent, thus promoting water supply later into the spring and early summer snow melt season.

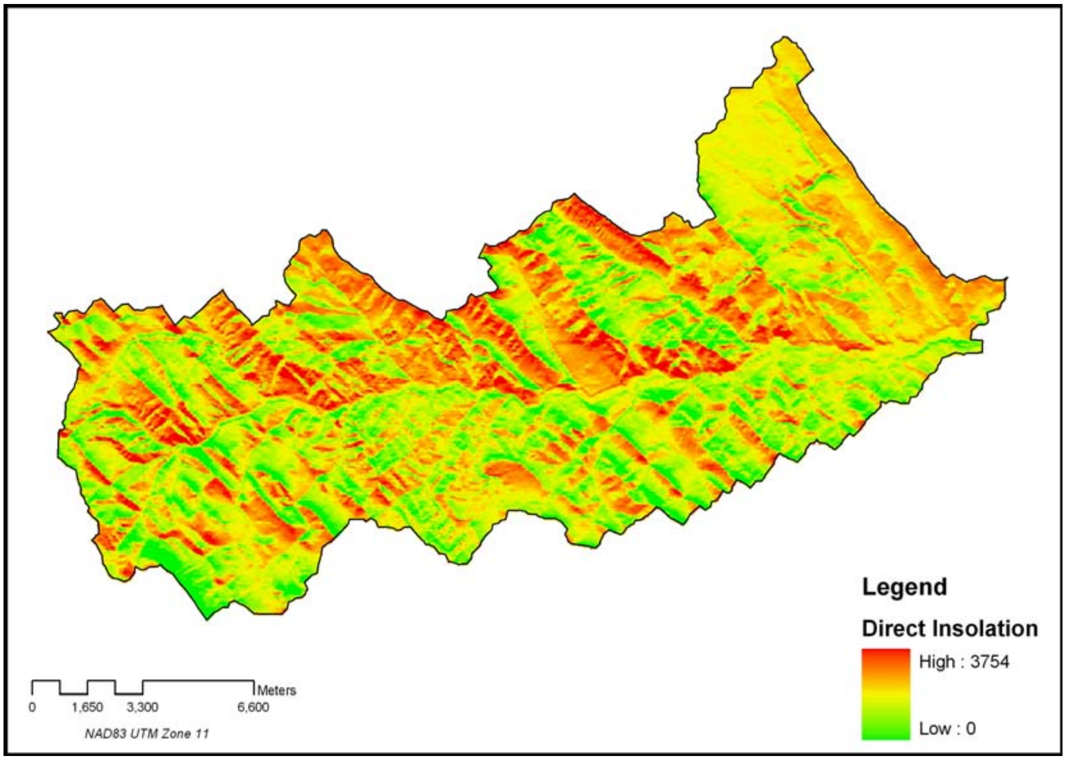

Figure 9: Direct Insolation map of Brown Creek watershed derived using GIS Solar Analyst (units: WH/m^2).

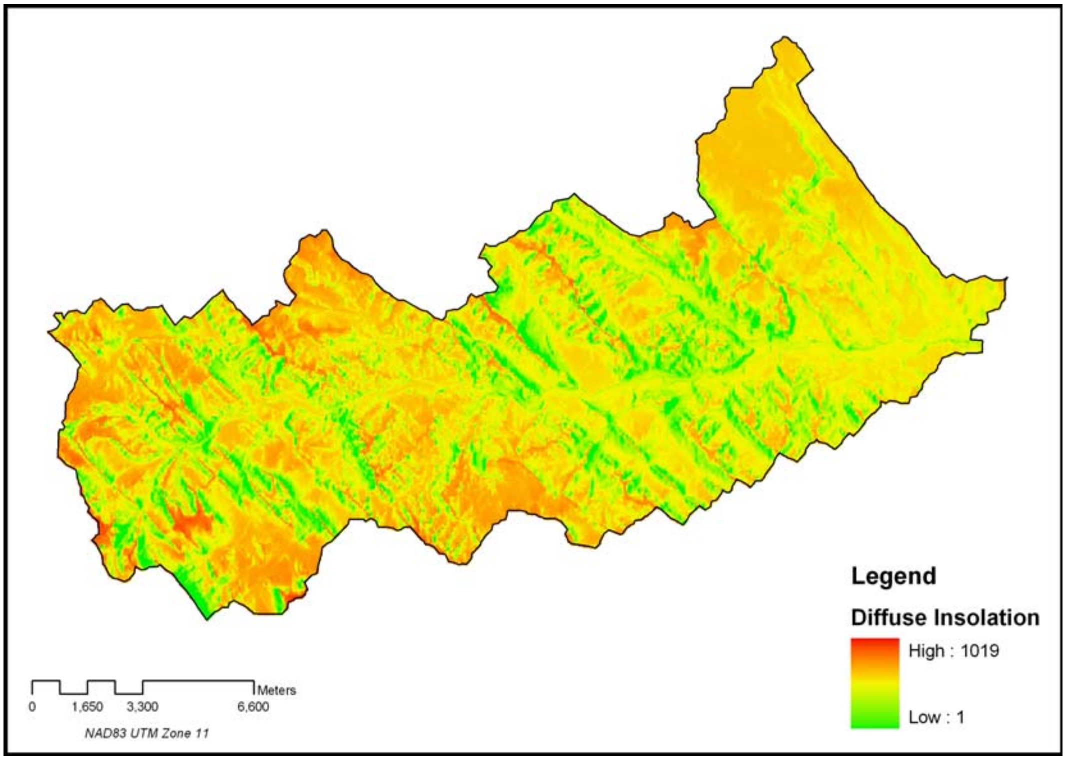

Figure 10: Diffuse Insolation map of Brown Creek watershed derived using GIS Solar Analyst (units: WH/m^2).

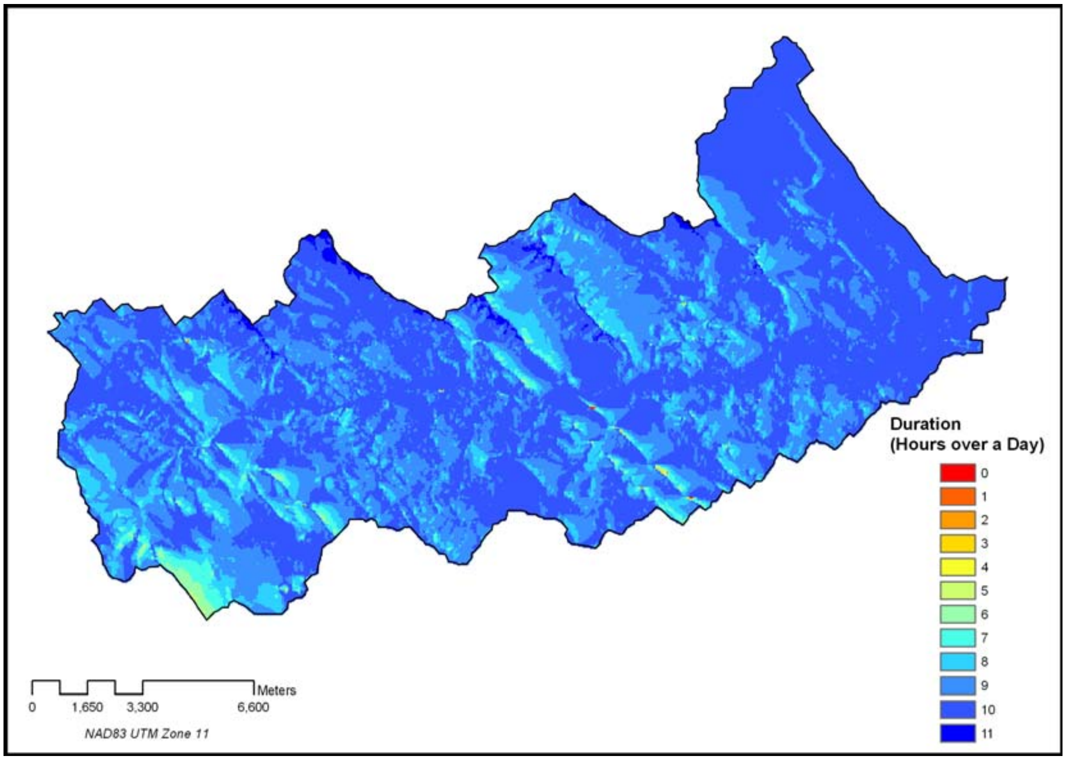

Figure 11: Insolation Duration (hours per day) map of Brown Creek watershed derived using GIS Solar Analyst.

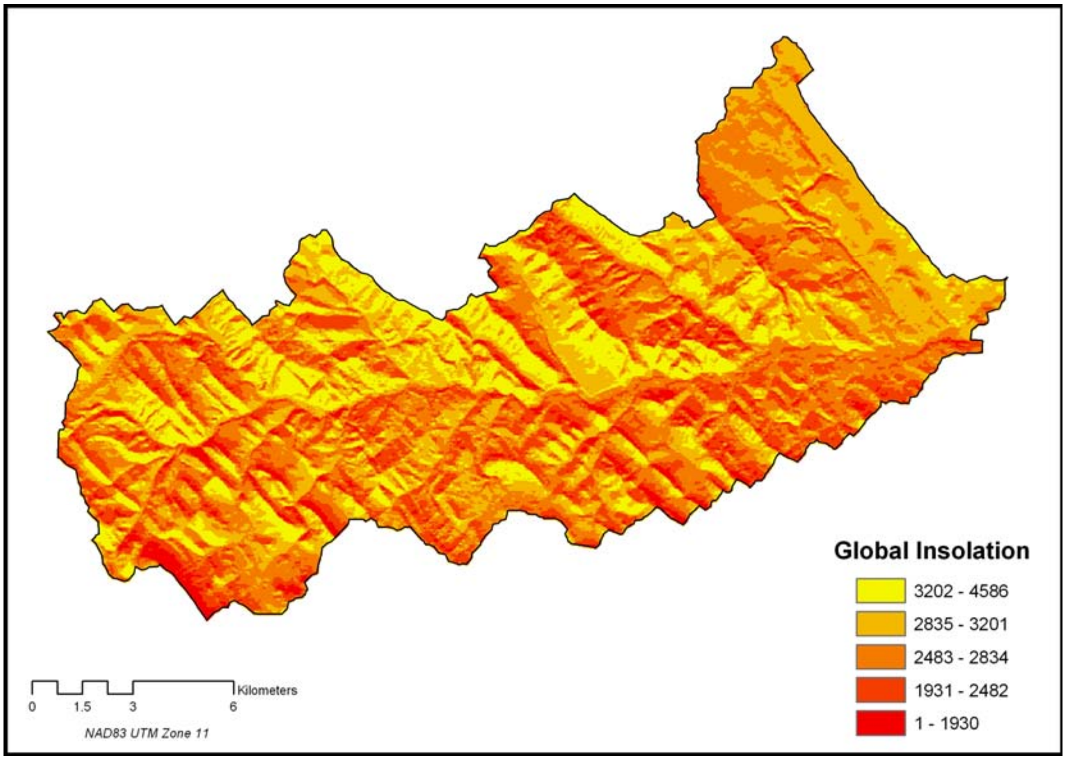

Figure 12: Insolation Index (INI) map of Brown Creek watershed derived using GIS Solar Analyst (units: WH/m^2).

4.0 CONCLUSION

In this paper, we have presented a series of topoclimatic indices derived for an alpine watershed at Brown Creek Alberta, located in the Front Range of the Rocky Mountains. These indices, derived as a function of geomorphometric variables from a digital elevation model and from meteorological station data, provide important information on topographic and climatic controls on surface hydrological features. Specifically, the indices derived here have been designed to be interpreted with respect to precipitation, wind, temperature and solar radiation that are collectively important for monitoring and understanding hydrological processes in mountain watersheds over different fundamental scales. Further, they provide spatially explicit, comprehensive information that complements point-based field studies that are characteristically sparse in distribution. The ability to derive these indices at high spatial resolutions throughout large, regular grids is also advantageous given the remote, inaccessible and rugged terrain that typifies mountain ecosystems. These indices are ideally suited for analysis with satellite remote sensing imagery to further augment the derivation of hydrologically important information such as landcover, surface roughness, vegetation density and interception which can then be related to and used with bulk streamflow analyses and predictions, coupled surface and groundwater hydrological models, and in studies of climate change involving multi-temporal satellite image archive data.

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