INTEGRATING DRAINAGE ENFORCEMENT INTO EXISTING RASTER DIGITAL ELEVATION MODELS

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by

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ABSTRACT

Initial evaluation of the "hydrologically correct" HYDRO1k (2001) data set, found that the drainage network derived from the topographic data using the TOPographic PArameriZation (TOPAZ) software was inconsistent with the blue line data in the National Atlas of Canada data. Further analysis found minor elevation errors in the HYDRO1k DEM were causing drainage network inconsistencies in some relatively flat and low elevation areas. Implementation of the Australian National University Digital Elevation Model (Hutchinson 1989) algorithm for drainage enforcement corrected the drainage networks, however, it adversely affected the DEM characteristics by substantially lowering high elevation values and created a general smoothing effect across the DEM surface. It was felt that a method that captures ANUDEMs drainage enforcement capabilities, but limits the effect on the surrounding DEM outside the drainage network area would be beneficial.

The focus of this project was to develop a new method for the development of a hydrologically correct Digital Elevation Model (DEM). Specifically, this project uses a presently accepted procedure, ANUDEM, developed by Hutchinson (1989), and builds upon it using a series of drainage network based buffers. The new method uses a simple distance weighting of elevation values based on proximity to the drainage network to weight elevation values closest to the drainage network more heavily to ANUDEM calculated values and to give ANUDEM values less weight as the distance moves further away towards the edge of the buffer. This approach effectively minimizes the effect of ANUDEM processing on areas away from the drainage networks.

Three drainage basins DEMs were used to test the new procedure, each exhibiting a particular problem for hydrological modeling and automated delineation of drainage networks. The first DEM was extracted from the HYDRO1k database and represented the Saskatchewan River Basin at a resolution of 1 km. It contained minor elevation errors that gave rise to incorrect drainage delineation.
The second DEM represented the Mackenzie River Basin at a resolution of 2 km and, as part of an earlier scaling study, had been derived by aggregation of an initial 1 km resolution DEM. The aggregation process introduced several drainage network errors. The third DEM represented the Snare River Basin at a resolution of 100 m. This basin had a very small elevation range and chaotic drainage pattern which make it very difficult to model.

Following implementation of the new procedure for the Saskatchewan River Basin and the Mackenzie River Basin, TOPAZ provided drainage networks that were consistent with the corresponding blue line networks in the National Atlas of Canada data set. Examination of the DEM characteristics found that effects of the new procedure on DEM characteristics were minimal. The range of elevations was maintained and the mean elevation of the DEM is statistically unchanged using a 1, 3 and 5 cell buffer width. Using 10 and 20 cell buffers, also provided correct drainage networks, however, effects on the DEM characteristics started to increase. In the case of the Snare River Basin, ANUDEM was unable to process the DEM for the Snare River Basin presumably because a threshold of drainage network complexity and topographic relief was exceeded.
ACKNOWLEDGEMENTS

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LIST OF ACRONYMS

ANUDEM.... Australian National University Digital Elevation Model
CSA......... Critical Source Area
DCW......... Digital Chart of the World
DEM......... Digital Elevation Model
DEMON...... Digital Elevation Model Networks
DEDNM...... Digital Elevation Drainage Network Model
DLG......... Digital Line Graph
DTED........ Digital Elevation Terrain Data
EROS........ Earth Resources Observation Systems
GCM......... Global Circulation Model
GIS......... Geographical Information Systems
GPS......... Global Positional System
GTOPO30..... Global DEM 1km resolution
HYDRO1k..... Hydrologically correct DEM 1km resolution
MSCL........ Minimum Source Channel Length
M/W......... Moore Wilson sediment transport capacity index
NIMA........ National Imagery and Mapping Agency
NSTAT....... Network and Sub-watershed Statistics
NTS......... National Topographic Series
PARAM....... Sub-watershed PARAMeterization
RASBIN...... RASter to BINary Network
RASFOR...... RASter FORmatting
RASPRO...... RASter PROcessing
RUSLE - LS. Revised Universal Soil Loss Equation Length Slope
TIN......... Triangular Irregular Network
TOPAZ....... Topographic ParameteriZation
USGS........ United States Geological Survey
CHAPTER 1

Introduction

Topography influences biological and atmospheric activity and hydrological systems; it governs water movement over and through the soil. Topography influences soil physical and chemical properties, as well as its erosion potential (Hutchinson 1997). Due to the need and desire to perform large-scale analysis of topography, automated techniques of landscape evaluation are being increasingly utilized. DEMs are being used more regularly for digital analysis of landscape topography (Hutchinson 1997). However, limitations and the accuracy of regular grid elevation models leads to error when DEMs and stream data of different origins are merged, and can lead to misrepresentations of topographic systems (Hussein and Schwartz 1997). Most automated delineation of drainage network procedures include modules for correcting DEM surfaces in order to correct for spurious depressions and flat areas, features that are usually deemed to be artifacts of the sampling process. “Stream-burning” or incorporating digitized stream networks into the DEM have been useful to correct for larger errors that fall outside depression and flat area correction algorithms. Drainage enforcement and “stream-burning” often alter the landscape, especially in high elevation areas as well as along stream channel boundaries. The derived channel properties may still be incorrect despite all of these correction procedures.

The purpose of this project is to develop an alternative procedure that will create a hydrologically correct digital elevation model (DEM) by merging existing DEM and vector line data, also known as blue line stream data. While the
procedure will use a commonly accepted enforcement algorithm, it will further build on known procedures and improve the results especially by preserving the DEM outside of the blue line network.

The four objectives of the project are:

1. Compare "blue line" or vector stream networks, TOPAZ delineated networks, and Australian National University Digital Elevation Modelling (ANUDEM) drainage enforcement program stream networks in an attempt to isolate differences in stream line characteristics and networks derived from drainage enforcement

2. Develop a hydrologically sound DEM by smoothing a stream network into the surrounding elevation data using a new algorithm

3. Compare the new hydrologically correct DEM to a DEM developed from ANUDEM in order to determine differences between an accepted method of drainage enforcement and a new procedure for drainage enforcement

4. Examine three different DEMs exhibiting modeling problems; one exhibiting low relief errors that are uncorrected by standard drainage enforcement; one exhibiting grid cell aggregation where drainage network definition and basin boundary are non-reproducible; and a third basin exhibiting low relief in the Canadian north were drainage issues prevent accurate automated delineation of hydrologic parameters

The four objectives will be examined using three evaluation techniques. The original DEMs, and resulting DEMs will be compared to a conventional method of "stream integration" using ANUDEM where vector stream data or blue line data is used to enforced drainage into a DEM. The hydrological characteristics of a DEM that has had enforcement applied is hypothesized to be significantly
different from its original DEM source before enforcement has occurred. The differences resulting from the two different methods will be examined and evaluated using descriptive statistics as an initial assessment of DEM characters.

The second, is a visual comparison of blue line stream data taken from United States Geological Survey Digital Line Graph data (USGS DLG), The Canadian National Atlas data and raster stream networks that have been developed from TOpographic PArameteriZation (TOPAZ). Stream networks will be examined for major differences on both the macro and micro scale. Blue line stream networks will be used as input into ANUDEM (Hutchinson 1988) and the resulting “hydrologically correct” DEMs will be visually examined for deviations from the original DEM.

The third analysis, is an examination of an elevation grid for each of the models runs. The elevation grid will be used to identify where deviations in elevation value occur resulting from the different process. This matrix will help to identify the effect the proposed procedure will have on the elevation values. It is suspected ANUDEM has a widespread influence across the entire DEM surface effectively unnecessarily smoothing elevation features that do not need to be processed.

The project will examine three drainage basins. the Saskatchewan River Basin, specifically the South Saskatchewan Drainage Basin, the Mackenzie River Basin aggregated at two different aggregation levels, and a portion of The Snare River Basin, will be used to test the procedure. The three basins display different topographic qualities. First, the Saskatchewan River Basin exhibits a glacially altered prairie drainage environment. Secondly, the Mackenzie River Basin, which possesses a more diverse landscape, however, linear aggregation has been applied and the drainage networks and basin boundaries have been altered. Third, The Snare River Basin, located near Yellowknife, possesses permafrost and northern drainage issues that will be examined. The algorithm will be
testable for accuracy in landscape exhibiting high, low and flat relief as present in
the different drainage basins. Similarly results from different resolutions and
basin size and complexity will also be evaluated.
CHAPTER 2
Literature Review and Background

2.1 General Background

For more than ten years Geographical Information Systems (GIS) have been used for processing distributed hydrological models. Distributed models allow for spatial analysis of hydrologic variables because they account for the spatial variability of physical properties (Turcotte et al. 2001). GISs have been used and evaluated for a range of applications such as soil studies, integration of terrain and radar-rainfall data into watershed models; and coupled with hydrologic modeling for the purpose of stream hydraulic analysis (Tate et al. 2002). GIS have been found to be an acceptable alternative for hydrologic modeling that simplifies data processing (Garbrecht et al. 2001, Ogden et al. 2001)

Development of GIS technology has provided physical and social scientists with a tool that provides automated data capture, storage, management, retrieval, analysis and display of data (Walsh et al. 1998). GIS provides a method to examine spatial and non-spatial relationships such as neighborhood, overlay, and attribute operations. They provide a technique for the representation of landscape data arrays through geographically registered attributes and allow for convenient display of those coverages. GIS allow for visual analysis, as well as provide a technique through which statistical analysis can be applied to spatial and temporal patterns (Walsh et al. 1998).
GIS availability in conjunction with an increase in access to digital information has renewed the interest in watershed modeling. Digital Elevation Models (DEM) have become the basis for most modeling procedures to date. The process of automated extraction of topographic features has become very robust and is now widely accepted (Jones 2002). This is apparent in most GIS packages where topographic analysis tools are now being utilized (Stocks and Wise 2000).

Accuracy errors within the DEMs are becoming increasingly important as modelers rely more heavily on their use. Several methods of automated extraction attempt to correct for some of these errors. DEM surfaces are pre-processed prior to calculating topographic indices in order to remove spurious depressions and flat areas (O’Callaghan and Mark 1984, Jenson 1989, Garbrecht and Martz 1997). However, automated delineation of drainage networks from DEM can produce networks that differ from known “blue line” networks (Saunders 1999). Main causes of these errors are often minor errors in the DEM elevation values and constraints caused by the horizontal and vertical resolution of the data used for the generation of the DEM.

“Stream burning” and drainage enforcement algorithms such as ANUDEM attempt to solve for these errors by incorporating digitized stream networks or “blue line” networks into the DEM surface. Nevertheless, these methods can produce undesirable effects as areas along the channels are subsequently affected by these procedures (Saunders 1999, Wilson and Gallant 2000).

This chapter will review DEMs, their accuracy and various techniques of automated extraction and drainage enforcement. Case examples will also be provided where commonly accepted procedures have failed in modeling specific problem areas, giving the reader insight into common problems arising from DEM errors or manipulation.
2.2 Digital Elevation Models (DEM(s))

2.2.1 General Overview

Geographical Information Systems (GISs) are currently being utilized to develop and store a variety of topographic data for use in water resource analysis, biological, social and several other natural and social science modeling applications (Lacroix et al. 2002, Moore et al. 1991). The widespread availability of GIS and electronic spatial data allows for increased digital evaluation due to its increase in speed, cost efficiency and ability to reproduce results (Lacroix et al. 2002). As a consequence of the increased availability of spatial data, the modeler now has to evaluate the data, its source and its structure in order to determine if it is applicable or sufficiently accurate for the specific modeling task it is required to perform (Garbrecht et al. 2001).

There are two major types of GIS data structures: vector and raster. Vector data represents spatial data as points, lines or polygons that are constructed as a continuous series of precise positions. This data is analogous to the National Topographic Series (NTS) maps of contours, roads, watercourses, dwellings and other physical features (Clarke 1995, Garbrecht et al. 2001).

Unlike the vector data where each point or series of points has associated attributes, the data in a raster is stored as a grid cell. Data values apply to the area represented by the grid cell. The grid cell is referenced in the array according to its column and row number and the boundary of the raster cell is the only portion of the cell that has a spatially referenced location with known co-ordinates (Garbrecht et al. 2001). Raster and vector data both have specific advantages and disadvantages. Vector networks are best suited for representing network structures and connected features with distinct boundaries. Raster structures are advantageous for representing smooth and continuous features. Most modern GIS packages can process and overlay both data structures (Garbrecht et al. 2001). Topological information showing how features area spatially related to
neighboring features are expressed by both raster and vector data structures (Clarke 1995, Garbrecht et al. 2001).

Most of the world has been digitized into elevation values and DEMs. DEMs are a broad term that is commonly referred to and used as a representation of the earth’s topography. Topography description is not solely represented as a DEM but can also be represented by mathematical expressions. There are three main types of DEM data structures. These structures are grid, triangular irregular network (TIN) and contour based (Moore and Grayson 1991). The grid structure is a matrix of cells as a raster network with elevation values associated with each cell. The TIN network is a series of interconnected triangles. Each triangle is associated with an elevation and location at each vertex and the triangles interconnect to create a continuous surface. The contour based DEMs consist of digitized contour lines with associated co-ordinate pairs and an associated elevation value. The data is often referred to as a Digital Line Graph (DLG) (Walker and Willgoose 1999, Wilson and Gallant 2000, Garbrecht et al. 2001).

![Figure 2.1: Methods of digital elevation data structuring. (a) square grid netting a moving 3 by 3 sub matrix centered on a node. (b) triangulated irregular network. (c) contour –based network. Source: Wilson and Gallant, 2000: p. 4](image)

DEMVs are most commonly available in the grid format. Contour data structures provide a very reasonable representation of landscape features unlike the raster format. They are extremely accurate for portrayal of streamlines and surface runoff, and use natural flow lines and contours to define drainage systems.
The main disadvantage of contour based DEMs are that they are a one-dimensional representation of a feature with two-dimensional attributes and that under-sampling may occur between contour lines (Hutchinson and Gallant 2000, Garbrecht et al. 2001). TINs require more processing than grids but can provide varying triangle size, which can be advantageous for representation of surface features. TINs because of their dense network of points in complex landscapes, can provide better stream channel definition in higher resolution terrain representations, and are especially useful for hydraulic analysis of river channels (Tate et al. 2002). The most common DEM type is the grid based DEM. The grid is computationally simple and efficient compared to the other two types. The disadvantage of the grid based DEM is that grid cell size cannot vary within the grid array. As a result, the user must decide which grid resolution is best for the specific task to be performed. The grid resolution decision needs to be based on the roughest terrain observed in the catchment area (Walker and Willgoose 1999, Garbrecht et al. 2001).

DEM: ordered arrangement of values representing spatial sequencing of terrain based attributes. The DEMs array of elevation points represents the distribution of elevation points associated with these values above some pre-determined datum in the landscape (Moore et al. 1991). Most users of DEMs must rely on outside agencies for delivery of this digital information as they do not have access to the field, Global Positioning System (GPS), or other primary data themselves. This digital information is usually published by various national, provincial, and state governments as DEMs or as topographic contour data that has yet to be processed into a DEM (Hutchinson 1989, Moore et al. 1991, Walker and Willgoose 1999). Many of the published DEMs have inherent errors, as the DEMs created are only as accurate as the information used to develop them. The USGS DEMs, for example, use "true elevations" from topographic contour data; however, there are inaccuracies in the contour data that are carried through to the final data source (Moore et al. 1991).
2.2.1 Digital Terrain Models and Terrain Analysis Using DEMs

DEM quality and DEM derived products directly effect digital terrain analysis applications. The most important factors in DEM quality are: terrain roughness and complexity; terrain modeling aspects such as sampling density; DEM collection and interpolation methods; grid cell size and spacing; precision or vertical resolution; and the nature of the algorithms used to derive the terrain parameters (Hengl et al. 2004). It is paramount for digital terrain analysis that a DEM resembles the “true” terrain, not the absolute accuracy of the elevation values. The accuracy of the terrain parameters is more a function of the “relative accuracy” or how the DEM resembles the actual terrain patterns and flow processes, than the “absolute accuracy”, and how accurately digital data “fits” the real world (Hengl et al. 2004).

There are a number of parameters that are important for the description of terrain (Table 2.1). The three most relevant are relief, slope and wavelength or extent of terrain (Fredrikson et al. 1985). Other attributes that are often calculated are catchment area, plan and profile curvature and aspect (Wilson and Gallant 2000). All these variables may be derived from the three different data structures mentioned in the previous section.

There are several different scales of source topographic data used for modeling. Each model type is supports a specific scale (Figure 2.2). Most hydrological, geomorphological, and ecological studies have occurred at the global, micro, and nano-scale levels (Wilson and Gallant 2000). Meso and topo-scale studies have been relatively less studied despite environmental problems that arise at these
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<th>Hydrologic Significance</th>
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<td>Elevation</td>
<td>Climate, vegetation type, potential energy</td>
</tr>
<tr>
<td>Upslope height</td>
<td>Mean height of upslope area</td>
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<tr>
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<tr>
<td>Catchment length</td>
<td>Distance from highest point to outlet</td>
<td>Overland flow attenuation</td>
</tr>
<tr>
<td>Profile curvature</td>
<td>Slope profile curvature</td>
<td>Flow acceleration, erosion, deposition rate</td>
</tr>
<tr>
<td>Plan curvature</td>
<td>Contour curvature</td>
<td>Converging/diverging flow, soil water content</td>
</tr>
</tbody>
</table>

Table 2.1: Primary topographic attributes (adapted from Grayson et al. 1991)

different levels of scale such as soil erosion and non-point source pollution. Surface morphology effects catchment hydrology as well as slope and aspect, which are the most important controls acting at the topo-scale level. Their effect on land surface development includes soil development, which in turn directly effects nutrients and water availability for ecological processes (Wilson and Gallant 2000). At each scale different processes dominate and it is important to determine how they effect the different variables at the different scales. Hydrological and morphological “correctness” can eliminate some of the flawed assumptions that are carried forward for models that are being used at scales for which they have not necessarily been developed (Wilson and Gallant 2000).
### Relative Scale

<table>
<thead>
<tr>
<th>Scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 10,000's km</td>
<td>Cloud cover and CO₂ levels control primary energy inputs to climate and weather patterns</td>
</tr>
<tr>
<td>1,000's km to 10,000's km</td>
<td>Prevailing weather systems control long-term mean conditions; elevation-driven lapse rates control monthly climate; and geological substrate exerts control on soil chemistry</td>
</tr>
<tr>
<td>100's m to 1,000's m</td>
<td>Surface morphology controls catchment hydrology; slope, aspect, horizon, and topographic shading controls surface insolation</td>
</tr>
<tr>
<td>1's m to 100's m</td>
<td>Vegetation canopy controls light, heat, and water for under-plants; vegetation structure and plant physiognomy control nutrient use</td>
</tr>
<tr>
<td>&lt; 1m</td>
<td>Soil microorganisms control nutrient recycling</td>
</tr>
</tbody>
</table>

**Figure 2.2:** Scales at which different biological and physical systems are operating. *Source: Wilson and Gallant, 2000: p. 2*

Surface specific point elevation data is the primary data source for most interpolation techniques. The data is derived from gridded DEMs or from field data such as GPS and enhanced by photometric stereo models (Wilson and Gallant 2000). This data source is well suited for small catchment areas and is rarely used for larger areas. It is best suited and most efficiently utilized for modeling features coarser than the toposcale level (Figure 2.2).

Large area terrain representation is most commonly provided by contour and streamline data. There are some disadvantages to using contour data as outlined in the DEM section. Contour and streamline data is most efficiently used for fine to coarse toposcale modeling.

The last major data source is remotely sensed elevation data. DEMs are generated by interpretation of data from high altitude based methods (satellite imagery or aerial-photographs). These models provide broad spatial coverage but have specific limitations. Satellite based elevation measurements are generally
very high-resolution imagery with overlapping coverages. This allows for parallax measurements to calculate elevation values. Ground-truthing needs to be performed to accommodate the random errors generated by data collection from these methods (Wilson and Gallant 2000). Remotely sensed data is most commonly used for the finest scale modeling (micro and nano-scale levels).

It is important to consider data sources and grid resolution for terrain analysis. Many attributes are sensitive to these. A grid resolution that is too low tends to over-simplify the drainage network, in essence, overly smoothing landforms, thus eliminating terrain landforms that influence key hydrologic processes (Wilson et al. 2000). Primary topographic attributes (Table 2.1) such as slope gradient and flow path tends to decrease while specific catchment area tends to increase with grid cell size. Similarly, secondary topographic attributes such as the Revised Universal Soil Loss Equation length-slope factor (RUSLE - LS factor) and the Moore/Wilson (MW) sediment transport capacity index increase with an increase in grid cell resolution (Wilson et al. 2000).

With new methods of modeling and DEM generation most primary topographic attributes are being modeled accurately. The main inaccuracies occur with catchment area attributes because this attribute can change significantly over very small distances (Wilson et al. 2000). DEMs also often contain errors in elevation that are ignored by terrain models and terrain analysis processes. An example of this can be illustrated in high elevation areas where drainage networks and flow routing is most accurate. Alternatively, where low elevation areas exist, small errors in elevation values lead to very inaccurate networks and flow direction. Similarly, grid cell size and changes in variability within grid cells can cause modeling inaccuracies. Development of better DEMs will provide better terrain data for terrain analysis (Wilson et al. 2000).
2.2.2 DEM Accuracy

With the availability of digital data, accuracy has become a primary concern and is problematic for modelers. Data providers have been implementing accuracy standards and publishing these standards with their data (Hunter and Goodchild 1996, Lopez 2000). The DEM provides fundamental data from which variables such as elevation, slope, aspect, channel gradient, basin boundary and stream networks can be extracted (Clarke and Burnett 2003). DEM accuracy can have significant effects on extracted variables and these can have profound effects on model output (Bolstad and Stowe 1994).

Vertical error in elevation models can generate runoff volume discrepancies, as well as erroneous peak runoff periods (Kenwood et al. 2000). Errors in the original data sources can be magnified in product development. Slope errors, for example, have been found to increase dramatically in larger processed DEMs following processing procedures (Bolstad and Stowe 1994). Horizontal error has also been recognized in the literature and has been found to cause problems for spatially distributed hydrological models. Horizontal error, due to its influence on slopes and contribution area, will ultimately effect topographic index values (Zhang and Montgomery 1994). Increasing grid resolution further influences the topographic index. The effect on the topographic index is found in generally increasing minimum values, means, variance and skew of a topographic index distribution curve as resolution increases (Wolock and Price 1994). Wolock and Price (1994) have also determined that map scale has an impact on topographic index but to a lesser extent than grid cell size.

Several different methods for generating DEMs have been developed (Li 1992, 1993, Bolstad and Stowe 1994, Robinson 1994, Wilbert and Willgoose 1999, Kenwood et al. 2000). Despite the different methods, each one is influenced by three main factors: terrain character, sampling strategy, and interpolation method (Robinson 1994). National coverage DEMs are mainly derived from digitized
contour data, however, where this data is absent, automated correlation techniques that generate DEMs from stereoscopic imagery are employed (Sasowsky et al. 1992, Robinson 1994).

Terrain character is the first factor that can influence DEM accuracy. Wide ranges in topography on large continental scale DEMs and the differences in contour line interpolation procedures across international borders may compromise the representation of areas of low and high relief. Greater uncertainty in elevation values and absolute values may influence the slope and aspect of the DEM (Robinson 1994).

Sampling is the second factor that effects the accuracy of a DEM. Quality and resolution of the source data as well as sampling intensity and spacing of the terrain surface influence overall DEM accuracy following processing of this data. If over or under-sampling occurs, data may either be under-represented or a general data redundancy can result (Robinson 1994). Sampling effects will ultimately result in effects on the absolute vertical accuracy of the DEM which can also be effected by the accuracy of the horizontal control points used in the generation process (Robinson 1994).

The third factor having an impact on DEM accuracy is the interpolation procedure. Digitized contours have specific issues when interpolation is required. Unlike elevation points, contours represent a continuous string of data. This data is often used and weighted by the different processes employed to varying degrees, and in spite of the amount of detail that is used, adequate sampling density with a reasonable distributions of points is still required (Robinson 1994).
2.2.3 Vector Data Accuracy

DEM's are not the only digital data source containing errors. Vector data has a certain uncertainty associated with it as well. Errors in digitized data often result from map digitization and subsequent processing (Hunter and Goodchild 1996, Larson 2002). For this reason, Hunter and Goodchild (1996) have developed a method for vector uncertainty evaluation. The procedure requires the development of separate normally distributed random error rasters, generated from the input vector data. These rasters need to be directed in both the x and y co-ordinate directions. The two grids, when combined, produce a set of error vectors that are regularly distributed for the area to be evaluated (Hunter and Goodchild 1996). The procedure is repeated and a number of distorted data sets are created allowing evaluation of the vector uncertainty. For a more detailed description of the process see Hunter and Goodchild (1996). It is important that input data for DEM development needs to be scrutinized and evaluated along with DEM accuracy, to ensure the best available data is provided for the specific modeling task that to be performed.

2.1 Vector Hydrography Integration (Stream burning)

Development of commercial GIS packages has offered modelers the opportunity to adapt hydrologic models to efficiently use present GIS capabilities and functions. This is a distinct difference from the past when existing hydrologic models were typically incorporated into GIS packages (Maidment 1996). As models increase in complexity, vector and raster data are both used to account for both the vertical and horizontal flow of water, attributes that can be modeled most accurately using polygon boundaries and volume calculations as opposed to prior area based calculations. Similarly, vector data needs to be incorporated into the model structure to account for spatial-temporal dynamics needed for more complex models (Maidment 1996).
Most automated delineation programs or modules utilize a method of 8 directional pour points or the D8 method (Fairchild and Leymarie, 1991, Maidment 1996). This process uses the principle that each grid cell is connected to eight adjacent cells with respect to their steepest descent. Flow grids are derived from this method of evaluation on the elevation model, and as the model progresses, flow accumulation and upstream drainage areas are calculated. A more in-depth discussion of this method and other automated extraction programs is presented in Section 2.5. Some problems can arise, however, where the streams delineated from the flow grid do not coincide with pre-digitized map streams or where part of a drainage basin may empty into the wrong stream network. These issues can usually be resolved by using a “burn in” technique (Maidment 1996).

There are several methods of “stream burning” or “burning in” of the blue line (stream) network. Traditionally, the method either artificially raises the elevation of the elevation values surrounding the “blue line” network or decreases the values of the cells along the “blue line” network (Maidment 1996, Renssen and Knoop 2000). The process of integration of vector hydrography into DEMs or “stream burning” can be summarized in four steps (Saunders 1999). (1) Rasterization of a digitized stream network, (2) adjustment of DEM elevation values at the cells corresponding to the digitized stream network, (3) ensuring stream raster cell elevation values descend towards outlet points and (4) introduction of a defined elevation difference between the stream values and the surrounding DEM to be used to ensure the drainage channel is a lower elevation than the surrounding DEM. Although vector hydrography integration can be easily misapplied, reasonable watershed results can be achieved if basic rules are followed. Vector data should not be burned into raster data with a coarser resolution since results of integration into a coarser data layer may exhibit oversimplification of the stream network and major tributaries may be omitted (Saunders 1999).
The blue line data must be pre-processed prior to integration into a raster layer to ensure that a hydrologically correct drainage network is available. The drainage network must also exhibit a fully connected set of single lines without any breaks in the network. In order to create this network, the following steps need to be taken (Saunders 1999):

1) Removal of all off-stream lakes
2) Replacement of on-stream lakes with bisecting arcs
3) Removal of coastlines
4) Replacement of large streams displaying two banks with bisecting arcs
5) Removal of braided streams, delineating only the primary drainage course
6) Main stems of drainage paths must extend to the edge of the DEM
7) Removal of stray arcs, i.e., disappearing streams
8) Hydrographic features of close adjacent watersheds should also be burned into the landscape

There are various methods available for stream burning in DEMs and most have a common structure as all those methods: (1) convert a preprocessed hydrography layer to a grid representation of the stream network, (2) perform a thinning process on the grid to reduce the width of flow paths to the width of a single cell, (2) implement a method of burning the stream grid cells into the landscape and, (3) execute a FILL command to ensure that no in-stream elevation depressions occur (Saunders 1999). The process of stream burning is useful because stream networks and their locations are of primary importance in modeling as they reflect how water moves. The “burn in” process has been found to be extremely useful in coastline areas and areas with very flat and low relief where delineation has been traditionally difficult or where low elevations areas exhibit small but detrimental elevation errors (Maidment 1996).
2.3.1 Alternative Methods of “Stream Burning”

Saunders (1999) presents four examples of alternative methods to “stream burning” that can be used by ArcInfo GIS software and has been programmed in the Advanced Macro Language (aml). The first example, Fillburn.aml is an algorithm that assigns all stream grid cells the elevation values of the original DEM while assigning all off-stream values the DEM value plus 1000 units. Following processing, the manipulated DEM is reduced in elevation by 1000 units and the resulting drainage network is only one unit deeper than the amount of the maximum fill height (Saunders 1999).

The second algorithm, Expocurv.aml, manipulates elevation values in each stream reach by replacing them with values taken from a fitted exponential curve between the highest occurring elevation in the reach and the lowest elevation values in the algorithm. Further processing is required to account for short reaches where there is no elevation change. This must be performed to ensure that the highest elevation values in the reach occur at the most upstream cells and that the lowest are at the most downstream cells in the reach (Saunders 1999). This procedure requires a stream burning offset value that is determined by comparison of the fitted exponential elevation values with the lowest elevation values taken from a 3-by-3-cell neighborhood of the stream grid cells in the original DEM. The offset value is calculated as the maximum difference from that comparison incremented by one. All stream grid cells that have a result value of less than –1 are set to –1 (Saunders 1999).

A third “stream burning” algorithm referred to is the Tribburn.aml algorithm. This algorithm digitally replicates the vector hydrography network while mitigating watershed boundary distortion (Saunders 1999). This process abandons previous methods of a universal application of offset elevation values in favor of an iterative approach that smooths all down-stream occurrences of in-stream elevations that are higher than the elevation value of the most upstream
point in each reach. The resulting network represents the minimum stream burning offset value that will still allow for digital replication of the vector hydrography network (Saunders 1999).

The last "stream burning" algorithm is the Agree.aml algorithm. This process is a less computationally complicated alternative to other stream burning techniques. It can integrate a vector hydrography layer into a DEM and smoothes the elevations into the surrounding DEM employing a linear fit to the elevations inside a user defined buffer zone. This algorithm further allows for two user specified elevation offset values. The first is the smooth value for integration of the stream network into the buffer DEM and a sharp value for the integration of the buffer into the surrounding DEM (Hellweger 1997, Saunders 1999). This system is an alternative to conventional "stream burning" techniques, which simply drop elevation values to some given depth; however, there is still a component of dropping elevation values into the network and providing a simplistic "straight line" smoothing method of the stream into the surrounding DEM.

2.4 Drainage Enforcement

2.4.1 Australia National University Digital Elevation Model (ANUDEM)

ANUDEM is a program that enforces the blue line drainage network while generating a raster DEM from a variety of elevation sources (point elevation, contour elevation, existing DEM). There are several methods used to fit gridded surfaces to point elevations. One commonly used technique has been developed by Hutchinson (1988, 1989) and is used by a common GIS package, ARCINFO in its TOPOGRID module. This method uses an iterative finite difference interpolation method that employs irregularly spaced data as well as a multi-grid strategy that calculates DEMs at successively finer resolutions until a user-defined resolution is achieved (Moore et al. 1991, Hutchinson 1988, 1989).
The Hutchinson approach (1988) attempts to develop hydrologically accurate DEMs, by using blue line stream networks or automatic determination of flow patterns that are fitted to the DEM (Hutchinson 1988). ANUDEM (Hutchinson 1988) calculates DEMs as regular grids from irregularly spaced elevation data points, contour lines and streamline data and automatically removes spurious sinks producing a hydrologically correct DEM (Hutchinson 1988, 1991, 1997).

The drainage enforcement algorithm interpolates elevation data onto a regular grid by “minimizing a suitably weak roughness penalty on the fitted grid values and by simultaneously imposing constraints”. ANUDEM performs interpolation using the minimum curvature method (Hutchinson 1997). The drainage enforcement algorithm:

1. Imposes a drainage condition onto the grid elevation values and removes pits, thus ensuring that a connected drainage pattern is maintained and;

2. Uses contour lines and elevation values to ensure that the stream and ridges are correctly maintained.

The imposed drainage algorithm has been found to significantly increase the accuracy of DEMs, which have been generated from sparse data sets (Hutchinson 1997). The nature of the drainage enforcement algorithm is to find the lowest adjacent saddle point that leads to a lower data point and enforce a descending chain condition from each sink point via the intervening saddle to the lower sink, edge or data point on the other side of the saddle (Hutchinson 1997).

User specified tolerances adjust the strength of the drainage enforcement in relation to both the accuracy and density of the input elevation data. With proper setting of tolerance values, sinks that still persist in the DEM are accepted as features exhibiting significant elevation errors in the input data or as areas where
the input data is insufficient in density to reliably solve for the drainage characteristics of the newly fitted grid (Hutchinson 1997).

Streamline data can also be incorporated to obtain drainage enforcement requirements. Input of streamline data is useful where more accurate stream placement is required than those generated by automated methods (Hutchinson 1997). All elevation points that conflict with down slope flow along each streamline is removed. The process also uses stream lines as break lines for interpolation so that each stream line is at the bottom of the valley (Hutchinson 1997).

There are six file types ANUDEM can utilize for the generation of a hydrologically correct DEM:

1. Point elevation data
2. Sink point data
3. Stream line data
4. Polygonal line data
5. Contour line data
6. Lake boundary data

The program reads the data files and utilizes a simple multi-grid method to calculate grids at successively finer resolutions, starting coarse and moving finer to the specified resolution. As the process proceeds sensible drainage conditions are calculated and spurious pits are removed as outlined by the drainage enforcement algorithm (Hutchinson 1997).

2.5 Automated Delineation of Drainage Networks

Over the past three decades, automated extraction of hydrologic features has become a standard modeling practice. Previous methods of delineating drainage
networks and basins by hand using topographic maps have been pushed to the side in favor of automated methods, many of which have been incorporated into commercial GIS packages such as ArcInfo and ArcView or are coupled with and use GIS available tools (Lacroix et al. 2002). These processes have evolved from parallel processing operators that simply measure concave and convex pixels as potential stream and ridge points (Peuker and Douglas 1975) to more recent methods of "deterministic eight neighborhood cell" calculations used by most delineation programs today (Jenson and Domingue 1988, Martz and Garbrecht 1992).

With the development of drainage extraction programs two fundamental issues have arisen. The first is the method of deriving flow networks and upstream contributing areas. The second problem is the treatment of flat areas and depressions (pits) in the DEM. These "pits" confuse drainage enforcement algorithms and hinder flow routing (Jenson and Domingue 1988).

2.5.1 Flow Direction

Automated methods of extracting drainage networks and basins have been developed from several methods over the past few decades. Three main approaches have been developed. For instance, Band (1986) has redefined the original method proposed by Peucker and Douglas (1975) in which concave and convex pixels are examined and flagged as potential drainage network cells. These two methods are somewhat flawed in that often "pits" in the DEM cause connectivity problems and re-processing and thinning routines need to be performed to correct the drainage network. These two methods also do not incorporate a catchment area or critical source area function for network development and definition (Tarboton et al. 1991). O'Callaghan and Mark (1984), proposed the third and perhaps most widely used method (Martz and Garbrecht 1999). This method used three main procedures and calculations for identifying stream networks. The first procedure requires the removal of "pits" or artificial errors in the DEM, while the second determines the extent of the
drainage network and is controlled by the drainage accumulation area matrix. The third procedure is the development of a connected drainage network consisting of grid cells that exceed the accumulated area threshold (O'Callaghan and Mark 1984, Tarboton et al. 1991).

Single flow direction algorithms based on the premise of convergent flows are used most regularly in hydrologic modeling processes. These algorithms commonly use the D8 (Deterministic eight-node) method developed by O'Callaghan and Mark (1984). This method is the simplest, allowing flow to only one of its eight nearest neighbors based on the primary flow direction (Martz and Garbrecht 1998). The model permits flow outward to only one cell but allows flow inward from several upslope cells (Gallant and Wilson 2000). The method's simplicity and ability to model catchment boundaries and contributing area override its inadequacies in modeling divergent flow.

The D8 method possesses deficiencies in its ability to model flows where slope is steepest to more than one downslope cell. Cell slope is measured by the elevation difference between two grid cells divided by their distance apart. Due to the D8 method’s inability to calculate the direction of flow, a second level rule is applied which arbitrarily decides which cell is the downslope cell (Jenson and Domingue 1988, Martz and deJong 1988). The D8 method is also flawed since slope aspect is not followed precisely. Flow routing tends to be along preferred route directions of 22.5° based on grid orientation (Gallant and Wilson 2000).

The Rho8 method of flow direction determination proposed by Fairfield and Leymarie (1991) presents a randomized single flow direction method that introduces randomization to the D8 method. The algorithm is developed to produce mean flow directions equal to the aspect of the grid by breaking up parallel flow paths that result from the D8 method (Fairfield and Leymarie 1991, Gallant and Wilson 2000). The randomness that this method incorporates into the process introduces new cells into the network that have no upslope connection.
and because of the random nature of the algorithm, drainage networks cannot be reproduced in successive model runs. This method is no longer utilized because of these reasons (Gallant and Wilson 2000).

2.5.2 Alternative Flow Models

The Rho8 method described in the previous section is not the only alternative method used for flow routing practices. Multiple flow direction methods such as FD8 and FRho8 modify the original D8 and Rho8 methods and allow for flow divergence (Gallant and Wilson 2000). These methods use the D8 and Rho8 methods below points of channel initiation. Above these points, the algorithms will allow for the distribution of flow to multiple nearest neighbor nodes (Gallant and Wilson 2000). These two methods eliminate the D8’s parallel flow path problems while providing more realistic distributions of contributing area in the upslope areas (Gallant and Wilson 2000). Disadvantages to these algorithms arise from considerable dispersive flow effects in valleys, which are deemed undesirable for modeling purposes. These methods of flow routing require the use of the original D8 and Rho8 methods to model the flow in these areas. The incorporation of both single and multiple flow direction algorithms increases computational processing significantly (Gallant and Wilson 2000).

Another algorithm developed is the DEMON stream-tube method proposed by Costa-Cabral and Burges (1994). DEMON (Digital Elevation Model Network extraction) uses the aspect of the DEM by fitting a plane surface to each pixel that decides the downslope flow (Tarboton 1997). The flow is routed down a stream tube until the edge of the DEM or a “pit” is encountered (Gallant and Wilson 2000). This method is advantageous as the stream tube can expand and contract as they traverse divergent and convergent areas of the DEM surface and are not constrained to cell boundaries (Gallant and Wilson 2000). Overall surface flow routing is complete when all grid cells or pixels have been evaluated and flow direction assigned to them. This method is computationally complex and requires significant processing time (Gallant and Wilson 2000).
Different methods provide alternatives to the D8 method of flow routing; however, most models still utilize the D8 method. The D8 method has been found to produce consistent drainage patterns from convergent flow conditions and is consistent in calculating contributing area and spatial representation of sub-catchments (Martz and Garbrecht 1998).

All flow algorithms require descending elevation path for flow on a surface. Pits in the DEM surface or “pits” and depressions where grid cells occur without a lower neighbor provide a barrier to the algorithm (Gallant and Wilson 2000). There have been a variety of procedures developed to overcome these barriers, most of which require some level of pre-processing of the DEM surface (Gallant and Wilson 2000, Martz and Garbrecht 1999, Tribe 1992). The next section will briefly discuss these methods.

2.5.3 Depressions and Flat Areas

Depressions or pits have been identified in DEMs as spurious features that arise from automated interpolation procedures and have been traditionally thought of as under-estimation errors (O’Callaghan and Mark 1984, Jenson and Domingue 1988, Martz and Garbrecht 1998). Previous methods that have been proposed to deal with these spurious features include a smoothing or averaging filter (O’Callaghan and Mark 1984) that fills shallower depressions but leaves the deeper depressions (Jenson and Domingue 1988). The second method is to fill the depression by raising the elevation of the depression cells to the elevation of the lowest cell on the depression boundary (Jenson and Domingue 1988, Gallant and Wilson 2000). While this method creates a depressionless surface, undesirable effects may result. The method ignores landscape form within the depression, which will have effects on the topography when the depression is greater than one cell. Many of these depressions occur in a valley bottom, and as they fill, flow routing across the flat area backwards may cause the stream network to deviate from the lowest part of the topography (Gallant and Wilson
A third procedure has been proposed to solve for these spurious features. Spurious features have been found to be a result of both over and under-estimation of elevation values (Martz and Garbrecht 1998). The over-estimation of elevation values effectively produces a “Dam” in the landscape that prevents downslope flow routing (Martz and Garbrecht 1998).

The depression filling procedure initially evaluates the DEM and locates cells for which no down flow direction can be assigned using the D8 method previously discussed. These cells are those that have no adjacent cells that are lower than it in elevation. Evaluating the DEM for these inflow cells without outflow increases the computational efficiency of the model by not forcing the evaluation of all depressions (Martz and Garbrecht 1999). The cells in the area contributing to this depression are evaluated and the cell with the steepest slope is selected as the outlet (Martz and Garbrecht 1999).

If the contributing area of a depression is found to contain a closed depression or one without an outflow then the breaching algorithm is invoked. Breaching can only occur where an area of higher elevation occurs between two areas of lower elevations, as in a dam. The process follows the assumption that this would be the mechanism in a physical environment if water were to overflow a natural obstruction (Martz and Garbrecht 1999).

The last stage in the process involves depression filling. Depressions are filled only to the level of the breached outlet. The result of this procedure creates a flat area, which consequently causes problems for the D8 flow routing method as these areas now have no downslope path (Martz and Garbrecht 1999).

A new flat area algorithm modifies elevation values in these flat areas on the assumption that drainage occurs both away from higher elevations and towards lower elevations (Martz and Garbrecht 1998). Two gradients are imposed on the flat surface; one towards areas adjacent to lower elevations, which encourages
flow to lower elevations, and one away from higher elevations (Martz and Garbrecht 1998). Elevation modification increments are made to these grids and are added together for a total increment value. This increment is then applied to the elevation of the cells of the flat area and the result is a surface that is no longer flat. The area contains topographic structure that is towards lower elevations and away from higher elevations (Martz and Garbrecht 1998). For a more detailed description of this process refer to Martz and Garbrecht (1992, 1993, 1998, and 1999).

2.5.4 TOPAZ

TOpographic PArameteriZation (TOPAZ) uses a DEM to identify and measure topographic features, define surface drainage, subdivide watersheds along drainage divides, quantify drainage networks and parameterize sub-catchments. It has been designed primarily for assisting topographical evaluation and watershed parameterization for the support for hydrological modeling and analysis (Garbrecht and Martz 1999b) and is typical of D8 based methods. TOPAZ incorporates depression filling and breaching and is widely adopted due to it being very robust.

TOPAZ uses the D8 method, the down slope flow routing and the critical source area (CSA) concepts for DEM manipulations. Drainage and flow direction of the DEM surface is defined by the steepest down-slope path from the center cell to one of its neighbors and is the basis to the down-slope flow routing concept (see section on automated drainage extraction). The CSA principle defines drainage channels as those raster cells that have an upstream drainage area greater than a threshold drainage area (Garbrecht and Martz 1999a, 1999b, and Martz and Garbrecht 1993, 1999). The CSA value provides a minimum drainage area from which a permanent channel is maintained.

The hydrographic segmentation portion of TOPAZ identifies the channel network (Garbrecht and Martz 1999b, Martz and Garbrecht 2003). The steepest down
slope path from each raster cell in the digital landscape determines the drainage of the DEM. The down slope flow routing concept determines the upstream drainage area at each raster cell and the channel network is defined as those cells with an upstream drainage area greater than a user-defined critical source area value or the drainage area at which a permanent channel begins. The resultant network is a fully connected, convergent and uni-directional down slope channel network (Garbrecht and Martz 1999b, Martz and Garbrecht 1992, 1993, 1998, 1999, 2003).

TOPAZ has the capability to generate a hydrographic segmentation and channel network with spatially varying characteristics. The network structure, drainage density and sub-catchment properties are heterogeneous across the drainage basin, representing differences in the separate areas in the watershed. This capability allows for spatial variation in hydrologic controls such as geology, soil type, vegetation and/or climate (Garbrecht and Martz 1999b).

Such capabilities as exhibited in TOPAZ “allow the generation of channel networks of different densities and resolution to meet the scale, needs and purpose of a particular application” (Garbrecht and Martz 1999b). Further analysis such as determination of the Strahler order of each channel link and the assignment of an identification number to each network node and channel link is possible (Garbrecht and Martz 1999b).

### 2.5.5 TOPAZ Modules

TOPAZ initially utilizes a pre-processing algorithm (Digital Elevation Drainage Network Model or DEDNM) to rectify commonly found spurious pits and errors resulting from over and under-estimations in the elevation data by using both the fill and relief imposition algorithms (Martz and Garbrecht 1998). Corrections made by the algorithm during DEM pre-processing are strictly limited to cells of depressions and flat surfaces as to not interfere with elevations found across the DEM surface (Garbrecht and Martz 1993, 1999b, Martz and Garbrecht 1999).
Following DEM correction of depressions and flat areas, surface drainage is calculated using the D8 method previously discussed. Flow vectors are assigned to each grid cell based on the steepest downslope flow. In cases where there is more than one cell with greatest slope the flow direction is assigned to the cell that is encountered first (Martz and Garbrecht 1992). The number of cells that flow into it calculates the upslope contributing area for each cell. This area is determined by following flow path designations along the steepest slope for each cell to the DEM boundary (Garbrecht and Martz 2000, Martz and Garbrecht 1992, 1993).

Following the pre-processing of the DEM hydrographic segmentation is performed. Hydrographic segmentation requires the initial calculation of the watershed boundary. This boundary is calculated from the flow path grid. The user must also define a watershed outlet in row and column format. This outlet and the flow vector grid cells that contribute to the outlet are coded as being in the watershed and are used to delineate the watershed boundary (Garbrecht and Martz 2000, Martz and Garbrecht 1992, 1993).

Drainage networks are derived from the watershed boundary grid as cells that have contributing area greater than a user-specified threshold (Garbrecht and Martz 2000, Martz and Garbrecht 1992, 1993). The critical threshold is referred to as the CSA value or critical source area for the watershed, which is the upstream area required for initiating a permanent channel (Garbrecht and Martz 2000, Martz and Garbrecht 1992, 1993). The defined channel is a fully connected downslope network but may contain very short links that are undesirable for the network (Martz and Garbrecht 1992, 1993). The MSCL or minimum source channel length algorithm is used to prune these short channel lengths, which are deemed spurious features consisting of valley indentations, gully outlets and other minor topographic indentations not usually classified as drainage networks. These spurious channels are usually Strahler first order...
streams and are pruned from the drainage network if they are considered below the MSCL value (Martz and Garbrecht 1992, 1993).

The fully pruned and developed network is assigned Strahler stream order numbers for each channel link. DEDNM calculates the stream link length and node locations for later analysis (Martz and Garbrecht 1992, 1993). The stream nodes defined by DEDNM have contributing area and link length values between nodes, and these values are used to calculate the sub-watershed values and boundaries (Martz and Garbrecht 1992, 1993). Channel length and watershed indices are tabulated and reported by DEDNM and drainage networks and boundaries are provided as unformatted grids that are reformatted by the RASter FORmatting (RASFOR) module in the TOPAZ program for end-use by the modeler (Martz and Garbrecht 2003).

RASPRO is the RASter PROperties function of the TOPAZ software system. RASPRO calculates the spatial properties regarding depressions and flat areas as well as reclassifies elevation values, and calculates the slope and aspect of each grid cell as well as enhances the visualization of the network and drainage divides. RASPRO provides other hydrologic properties and is not limited to those mentioned here (Garbrecht and Martz 2000).

Upon completion of the RASPRO module, data from DEDNM and RASPRO can be used by the RASFOR module, which reformats the hydrologic information into a GIS useable format. The unformatted DEDNM and RASPRO files can be reformatted into one or two-dimensional ASCII files or into GIS specific files. TOPAZ 3.1 supports both IDRISI and ARCINFO GIS file systems (Garbrecht and Martz 2000).

The RASter to BINary network (RASBIN) module converts the grid network to a binary network. This module converts complex junction nodes onto simple node junctions, allowing only two inflows per node junction. RASBIN calculates
statistics based on the binary network and can be performed after DEDNM has finished pre-processing. ASCII files produced by RASFOR are not needed for the RASBIN module (Garbrecht and Martz 2000). RASBIN output files are required for the Network and Sub-catchment STATistics (NSSTAT) module in TOPAZ.

NSSTAT calculates statistics for each channel link for both the raster and binary networks. Standard deviation, means, sub-catchment and channel network properties such as watershed drainage areas, number of channel links, drainage density and network composition are calculated (Garbrecht and Martz 2000). PARAM (sub-catchment PARAMeterization) also uses the DEDNM and RASPRO raster output files to calculate the sub-watershed parameters (Garbrecht and Martz 2000). This section on TOPAZ modules is only intended as a brief overview of the TOPAZ processing functions. For a more detailed description readers should view Garbrecht and Martz (2000) and Martz and Garbrecht (1992, 1993, 1998 and 1999).

2.6 Sample problems – Case Studies

Automated processing of DEMs can handle spurious pits and produce drainage networks that conform to the topography of the DEM. In examples where the automatically delineated networks do not match the “blue-line” networks, the automated methods have reflected the topography represented in the DEM. Methods of “stream burning” and vector integration attempt to provide mechanisms to correct the topography to match the “blue-line” drainage networks.

2.6.1 The Saskatchewan River Basin and DEM Accuracy

The HYDRO1k data set is deemed the “gold standard” for global DEM. However, automated delineation processes found examples in the South Saskatchewan River Basin where the automatically delineated networks do not match the “blue line” networks, despite preprocessing using the Hutchinson
(1988) ANUDEM algorithm and “blue line” data in an attempt to provide a global scale, hydrologically correct DEM. The constraints used are unknown, but evidently there are differences in drainage networks in some low relief areas (Figure 2.3). The blue line drainage networks have been incorporated into the DEM surface; however, pre-glacial drainage networks are still the preferred paths in the delineation process. ANUDEM may also cause smoothing in the higher elevation regions of the DEM that will have effects on topographic variables such as slope and aspect.

![Figure 2.3: Major discrepancies between National Atlas of Canada hydrography (Figure A) and the HYDRO1K derived from GTOPO30 hydrography (Figure B).](image)

The process of “stream burning” and drainage enforcement has provided an excellent tool for the correction of large-scale DEM drainage inaccuracies. Maidment (1996), Hutchinson (1988), Hellweger and Maidment (1999), and Renssen and Knoop (2000) have provided examples of drainage enforcement and “stream burning” procedures, all of which vary in complexity and success. It is hard to argue that these procedures are fatally flawed as they provide reasonable
results; nevertheless, there are obvious instances where the results are undesirable. "Burning-in" often creates unrealistic troughs in the elevation surface. Following delineation processes, it is apparent that some processes generate parallel drainage channels (Jones 2002).

2.6.2 The Mackenzie River Basin and Problems with Scale

Studies in scale have found that grid resolution effects stream networks delineated from DEMs (Wang and Yin 1998). Similarly, slope and aspect accuracy have been found to decrease with coarser grid cell resolutions (Zhou and Liu 2004). The present use of Global Circulation Models (GCMs) for global climatological studies and global water resource modeling has increased. GCMs use large scale DEMs for modeling different processes. For instance, stream flow is important for three main reasons. The first is that stream flow is important in landscape parameterization and landscape analysis (Arora et al. 2001) and is an attractive method of assessing GCM surface water balance at larger scale. Stream flow is relatively easy to quantify and can be used to evaluate a GCM climatologically. Secondly, stream flow modeling is important for continental scale rivers where outflow into oceans effects salinity, thus effecting circulation, convection and ice formation. Thirdly, stream flow is extremely important for modeling continental scale water management (Arora et al. 2001).

Coupled with the GCM concerns with scale is that recent studies have determined that simple linear aggregation scaling produces drainage networks and basin boundaries that are not consistent with original data sources (Armstrong and Martz 2002). As aggregation is performed, drainage network length and basin boundaries are reduced; similarly flow paths are changed and flow networks are spatially located incorrectly (McMaster 2002). Armstrong and Martz (2003) found that changes in the basin boundary and the delineation stream networks occur at 2 km grid cell resolution after one-step of aggregation (Figure 2.4) although most changes did not become significant until resolutions of 8 km was
reached. While the most significant changes occur at coarser resolutions, the changes in the network and basin delineation may be undesirable for hydrologic modelers especially, for local scale analysis.

Figure 2.4: Differences in basin boundary and blue line drainage between the National Atlas (A) and the aggregated 2 km grid cell DEM of the Mackenzie River Basin (B)

2.6.3 The Snare River Basin and Problems with Modeling Northern Hydrology

The third case study to be examined is an example of a sub-DEM extracted from the Snare River Basin. The area exhibits complex drainage networks with divergent flow patterns. The area exhibits extremely low relief and elevation changes and there is a certain degree of unknown internal flow mechanisms (Figure 2.5). Modeling these environments is difficult, especially at a larger scale and with more hydrographic detail.

Automated extraction of drainage networks differ dramatically from the blue line networks for the area. TOPAZ uses depression filling and deals with flat areas in such a manner that environments such as these that are extremely low lying and
have very chaotic drainage networks automated delineation will be problematic. TOPAZ processes the DEM in such a manner that it is no longer representative of the actual landscape.

Figure 2.5: The Snare River Basin (N.W.T.) represents an area with low relief and internal drainage creating significant problems for modeling. Image on right is a subsection of this basin.

2.6 Summary

The increased use of grid based DEMs has lead to a rising need for hydrologically correct DEMs. Automated delineation techniques are robust and effectively generate drainage patterns that reflect the topography held in the DEM. Many pre-existing DEM are available in which the known drainage network patterns (blue line) is not fully connected to the topography represented by the DEM. This reflects the fact that drainage enforcement was not used in generating the DEM or that previously accepted processes are erroneous. One way to correct for these errors is to re-generate the DEM using drainage enforcement procedures similar to ANUDEM. However, this will require using previously interpolated grid cell values as spot heights and will effect the entire DEM. Another approach is “stream-burning” which does not ensure that pre-
channel topography is consistent with drainage networks. These methods also tend to produce "canyon channels" and may produce unrealistic slope values along the channel.

Studies in scale have similarly shown errors in drainage systems as aggregation occurs, however there continues to be a desire to use large global size data sets. The need to preserve true drainage and basin characteristics is essential to accurately model the environment, while simultaneously being able to appreciate the advantages of using larger grid resolution for computational ease. A need to develop an approach that corrects DEM drainage issues and correctly preserves drainage networks when grid cells are aggregated is required. This research is intended to provide a new method, based on an existing commonly accepted procedure that will allow the hydrological correction of a DEM while preserving other equally important attributes present in the original DEM.
CHAPTER 3

Methodology and Study Area

3.1 Overview

Due to the errors found in DEMs that are deemed hydrologically correct (HYDRO1k 2001), an alternative procedure for correction of the DEM is being proposed. This new method will enforce “blue-line” drainage in an existing raster DEM while minimizing changes to the elevation values across the DEM. The method uses the Hutchinson (1988) ANUDEM technique but constrains the changes in elevation values to the immediate vicinity of the channel network. ANUDEM is applied to the National Atlas of Canada vector data (GeoGratis 2000) at a scale of 1:7,500,000, which closely resembles the HYDRO1k (2001) dataset and the HYDRO1k (2001) DEM of the Saskatchewan River Basin. The proposed method initially extracts the region along the rasterized blue-line (correct) stream network at 5 different buffer widths. These buffer DEMs are then applied to a distance weighting algorithm, which weights those values at the stream center more heavily towards the ANUDEM output and more heavily at the edges to the original DEM dataset, thus minimizing the effects ANUDEM has on the topography of the DEM.

The procedure will look at three examples of drainage network inaccuracies, and an evaluation of their result networks using TOPAZ will be conducted. The first
basin is the Saskatchewan River Basin, which shows deviations from the blue line data directly from the HYDRO1k dataset. Results following the Saskatchewan River Basin analysis show that optimum buffer width occurs between 3 and 10 km. Limits seem to occur at the 20 cell buffer width as the buffer width is often wider than the "true" ground distance between watercourses, performed at a grid resolution of 1 km. The analysis is performed for two more drainage networks of varying grid cell resolution and complexity. The second drainage network examined is the aggregated Mackenzie River Basin DEM (Armstrong 2002). Automated delineation techniques (TOPAZ) produce smaller drainage basin area and shorter channel length with increasing grid resolution; resolutions of 1 km, 2 km, and 4 km will be examined at the different buffer widths. The third basin that will be examined is the Snare River Basin. The DEM of Snare River area has a resolution of 100 m, as is common in many north American DEMs. However, the drainage network is very chaotic and dense. TOPAZ will be utilized to produce drainage networks to determine if automated delineation provides networks that are correct according to the blue line data for all DEMs following the alternative correction procedure.

3.2 The Drainage Enforcement Algorithm: ANUDEM

The ANUDEM drainage enforcement algorithm (Hutchinson 1988) attempts to interpolate DEMs using spot elevations, contour lines, blue line stream networks, lake and coastal shorelines that are fitted to the DEM (Hutchinson 1988). ANUDEM calculates DEMs as regular grids from irregularly spaced vector data and automatically removes spurious sinks producing a hydrologically correct DEM (Hutchinson 1988, 1997, Hutchinson and Dowling 1991).

The nature of the drainage enforcement algorithm is to find the lowest adjacent saddle point that leads to a lower data point and enforce a descending chain condition from each sink point via the intervening saddle to the lower sink, edge or data point (Hutchinson 1997).
User specified tolerances adjust the strength of the drainage enforcement in relation to both the accuracy and density of the input elevation data. With proper setting of tolerance values, depressions that still persist in the DEM are accepted as features exhibiting significant elevation errors in the input data, or areas where the input data is insufficient in density to reliably solve for the drainage characteristics of the newly fitted grid (Hutchinson 1997). For a more detailed description refer to the ANUDEM section in the Literature Review chapter.

The program utilizes a simple multi-grid method that calculates grids at successively finer resolutions, starting coarse and moving finer to the specified resolution. As the process proceeds, sensible drainage conditions are calculated and spurious pits are removed as outlined by the drainage enforcement algorithm (Hutchinson 1997).

3.3 Data Sources

Two main data sources were used for input into the ANUDEM Drainage Enforcement Algorithm. The hydrological blue line information at a scale of 1:7,500,000 was clipped for the study area from the National Atlas of Canada Database (GeoGratis 2000). The input digital elevation model (DEM) was taken from the HYDR01k data set that was derived from the GTOPO30 DEM for North America (HYDR01K, 2001).

3.3.1 Blue Line (Vector Hydrography) Data

Vector blue line data used for this model was obtained from the National Atlas of Canada Digital Data (Geomatics Canada 2000). The data used was the 1:7,500,000 series as this is the scale that most closely resembles blue line data offered with the HYDR01K DEM data set (HYDR01k 2001). The National Atlas data was developed for the national atlas of Canada data set and is derived from 1:250,000 National Topographic Series (NTS) and the International Map of
the World Series at a scale of 1:1,000,000. The data has a co-ordinate accuracy of +/- 5 km or 5 grid cells, which represent less than 1mm on a published scale map (GeoGratis 2000).

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Scale/Resolution</th>
<th>Projection</th>
<th>Geo-reference Information</th>
</tr>
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<td>1000 m resolution</td>
<td>Lambert Azimuthal Equal Area</td>
<td>Longitude Origin - 100°N</td>
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<td></td>
<td>Latitude Origin - 45°W</td>
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<td>1: 7, 500,000</td>
<td>Lambert Conformal Conic</td>
<td>Central Meridian - 95°N</td>
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<tr>
<td></td>
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<td></td>
<td>Datum - NAD27</td>
</tr>
</tbody>
</table>

Table 3.1: Geo-reference table for input data

3.3.2 Digital Elevation Model (DEM)

The DEM used in this study was extracted using ArcInfo GIS software from the HYDRO1k data series, which was developed from the GTOPO30 DEM data series. GTOPO30 data is a result of processing Digital Terrain Elevation data (DTED), United States Geological Survey (USGS) DEM’s, and several other large-scale continental DEM data. The larger resolution data was generalized to the 30-arc second horizontal resolution (GTOPO30 2001). Canadian elevation data for the GTOPO30 data set was derived from the DTED series, with a horizontal grid spacing of 3-arc seconds (90 m) and was originally produced by the National Imagery and Mapping Agency (NIMA), formerly the United States Defense Mapping Agency. Re-sampling and generalization of the DTED data using a 10 X 10 matrix resulted in accepting one representative elevation value (GTOPO30 2001). Topographic information from vector blue line data, such as the Digital Chart of the World (DCW) was converted into elevation grids. Spot heights, contours, stream lines, lake and ocean shorelines were input into ANUDEM (Hutchinson 1989), a surface gridding program designed for creating DEM’s from digital vector data using drainage enforcement. The result is a
hydrologically correct elevation model that represents terrain more realistically than other previously utilized interpolation methods (GTOPO30 2001).

The HYDRO1K is deemed a hydrologically correct DEM, which is used by many hydrological modelers as it provides a standard product for hydrological analysis. This DEM has been processed to remove elevation anomalies to promote correct hydrological flow. In the processing procedure techniques to identify natural sinks and preserve those natural sinks were utilized, and all spurious pits were removed. Following this filling of the DEM initial streamlines and basins were generated. To verify the DEM, these basins and streamlines were compared to existing digital line data (HYDRO1k 2001). The HYDRO1k data set is a composition of several DEM “tiles” from the GTOPO30 dataset that have been merged together to create a single DEM for all of North America (HYDRO1k 2001).

In the development of the HYDRO1k data set two main errors were identified in the DEM, the first error being the omission or inclusion of natural sinks features. In the case of identified errors, the included feature is removed and the case of a feature being omitted, the feature is reintroduced to the DEM (HYDRO1k 2001). The second error identified in the DEM, is error that prevents proper hydrological flow. These errors are either caused by DEM generation, re-sampling techniques, horizontal resolution (1 km) or vertical resolution (1 m) of the DEM (HYDRO1k 2001). Following examination of basin boundary and streamline data for areas of deviation in the vector hydrography, areas of the DEM that lead to error in hydrological flow are edited to correct flow and to ensure it flows in the proper direction (HYDRO1k 2001).

3.4 An Alternative Approach to Develop a Hydrologically Correct DEM

The flow chart in Figure 3.1 illustrates the different modules that were run using ArcInfo GIS, ANUDEM and ArcView GIS, in order to develop a hydrologically
accurate DEM. Since the input data for ANUDEM can consist of several different GIS software formats, ArcInfo GIS input files were chosen, as they performed well in terms of computer processing requirements and in speed in generating output results. Several other GIS software types are supported including Idrisi GIS (Hutchinson 1989); however, data set sizes proved limiting using less robust GIS software. ArcInfo GIS provided adequate grid processing capabilities for the procedure.

There are two types of input data needed for this two-pronged procedure (Figure 3.1). One line requires an input set of data in vector and grid format and the second is a grid based stream network which gives rise to the smoothing portion of the procedure. The initial step in the processing procedure is to obtain a data set in point values, or spot heights for the grid DEM, lake boundaries and stream-line data. A single spot elevation from each grid cell is then generated for each 1000 m X 1000 m grid cell. ArcInfo ungenerate files provide the best result for ANUDEM input files for this portion of the model run. After the initial input files for ANUDEM have been generated a raster representation for the National Atlas blue line data (scale 1:7,500,000) was generated. This layer will provide the input data for the smoothing algorithm portion of the procedure, which will be described later in the methodology.

ANUDEM input files, as expressed previously, are ungenerate files of spot elevations, streamline data, and lake boundaries. A set of tolerances needs to be set in ANUDEM for the generation of the input data for the smoothing process. The first tolerance, the roughness penalty is set at a value of 0.5. This level is appropriate for the spot elevations as it provides an interpolation mix of minimum curvature (good for contours) and minimum potential (good for spot elevations) (Hutchinson 1989).
Figure 3.1: Execution sequence for the alternative approach to develop a hydrologically accurate DEM
Elevation tolerances, the next threshold which needs to be set, is set at a value of 1 and 1600. The first number (1) indicates the accuracy of the elevation data. A number of test model runs was performed as the data accuracy of the HYDR01k is +/- 30m, and the best results were found to be at a 1 m setting for this value, despite calling for a 30m setting. The 1 m setting in essence calls for a more rigid enforcement of the hydrological characteristics in the DEM.

The second elevation tolerance (1600) can be set as high as the maximum elevation value, but is recommended to be set at close to one half the total relief values. In the case of the Saskatchewan basin 3548 m is the maximum elevation. The tolerance is very rarely triggered and prevents drainage clearance through unrealistically high barriers. The remaining settings were set at default values. Vertical and horizontal standard error was set at 1.0 and 0.0, respectively, with a maximum number of iterons being 40 (Hutchinson 1989).

The output of the ANUDEM model run provides the initial data set for the next step in the methodology, which is the development of an alternative hydrologically accurate DEM with a less intrusive altering of the DEM landscape. This initial step provides a standard data set for input into subsequent process in which ANUDEM results from stream buffer zones of varying widths are incorporated into the initial DEM. The rasterized drainage network provides a data set in which 5 buffered regions are generated. These are at 1, 3, 5, 10 and 20 cell buffer radii. The buffers are created using the ArcInfo GIS EXPAND command. For each of these buffered regions the DEM generated through the ANUDEM process is extracted. This provides subsets of elevation data that can be incorporated into the original DEM using a distance-weighting procedure. Such an approach will preserve the profile and contour curvatures in the area along the stream network. The result is a DEM that has had ANUDEM drainage enforcement applied to the buffered regions only.
The Euclidean distance grid is employed to calculate distances from all cells in the DEM to the raster blue line network. This Euclidean distance grid is processed using a distance query, based on the buffer width, and extracts a grid of distance calculations for the buffer region. The Euclidean distance grid and the distance query form the basis for the distance grid algorithm. The distance grid algorithm (Equation 3.1) is a reclassification grid that provides distance values that are used for calculating the percentage-weighting portion of the process. A distance-weighting grid (Figure 3.2 and Figure 3.3) is the result of this algorithm. This algorithm provides the distance grid needed for the weighting algorithm.

The output from Equation 3.1 is used in Equation 3.2 and provides the new hydrologically correct segment for the various buffered regions. This algorithm is the distance weighted average segment that is later merged into the original hydrologically incorrect HYDR01k DEM. Equation 3.2 provides a weighting technique that uses the distance weighting values from Equation 3.1. The process weighs values closer to the raster river network higher for ANUDEM values and less for original inaccurate elevation values, and as it grades out to the edges the original DEM values are weighted more than the ANUDEM imposed values. An example of the weighting algorithm output can be seen in Figure 3.4. The algorithm calculates elevation values, which are derived from their location in the distance grid. The distance grid dictates the percentage each DEM (ANUDEM and original DEM) contributes to the new elevation value. For example, if an elevation value is located at a distance that is 20% of the total buffer width distance, then 80% of the elevation value is taken from the ANUDEM output and 20% is used from the original DEM elevation value. Similarly, if an elevation value is located at a distance of 80% of the total buffer width distance, then 20% of the elevation value is taken from ANUDEM and 80% is taken from the original DEM value. This method minimizes the effect of ANUDEM on regions outside the river network and eliminates the effect outside the buffer, at the same time allowing for correction of inaccurate DEM values in the buffer for regions where the hydrography does not match known true blue line data sources.
Equation 3.1: Calculation of the weight at each cell

\[ W = L - \left( \frac{L - D}{L} \right) \ast L \]

where:
\( W \) = weight
\( D \) = Euclidean distance from channel
\( L \) = Buffer width

Equation 3.2: Calculation of new elevation value at each cell within the buffer

\[ Z_n = Z_a \ast \left( \frac{L - W}{L} \right) + Z_o \ast \left( 1 - \left( \frac{L - W}{L} \right) \right) \]

where:
\( Z_n \) = new elevation value
\( Z_a \) = elevation value from original DEM
\( Z_o \) = elevation value from ANUDEM generated DEM
Figure 3.2: Distance weighting grid for 1, 3, and 5 cell buffer widths. Distance values are in meters, and represent the distance from the blue line raster network within the buffered region. The grids are used to derive elevation values in the smoothing algorithm.
Figure 3.3: Distance weighting grid for 10 and 20 cell buffer widths distance values are meters and represent the distance from the blue line raster network within the buffered region. Grids used to derive elevation values in the smoothing algorithm.
Figure 3.4: Weighting algorithm grid for all buffer widths. Values are in meters above sea level, results indicate elevation values after the percent weighting has been applied to all cells in the buffered regions.
This last output created from the correction procedure is then merged using ArcInfo INSERTGRID module into the original DEM that had improper elevation values for the stream regions, in result creating a hydrologically accurate DEM.

3.5 TOPAZ: Topographic Parameterization, Digital Terrain Analysis

TOPAZ needs a grid DEM for the initial steps of hydrological delineation. The file given is a single column ASCII file. The control file for TOPAZ identifies the outlet for stream determination and other attributes such as Critical Source Area (CSA) and Minimum Source Channel Length (MSCL). The preprocessing algorithm of Digital Elevation Drainage Network Model or DEDNM rectifies commonly found spurious pits and errors resulting from over and under-estimations of the elevation data by using both the fill and relief imposition algorithms (Martz and Garbrecht 1993).

The hydrographic segmentation portion of TOPAZ identifies the channel network and is the module used most extensively in this study. TOPAZ provides the same output as is represented by HYDRO1K hydrography layer, as the methods utilized to develop the HYDRO1K data set are very similar to the processing algorithm employed in TOPAZ. TOPAZ is used on the resulting hydrologically correct DEM to determine the effects of the alternative approach and to determine the success of the model.

3.6 Study Area

Three river basins were chosen for this study. The first is the South Saskatchewan River Basin, the second is the Mackenzie River Basin and the third is the Snare River Basin (Figure 3.5). The South Saskatchewan River Basin has been chosen for the apparent disconnection between the “blue-line” data and the automatically
delineated drainage network. The Mackenzie River Basin was chosen for problems arising in differences in drainage network resulting from linear aggregation of grid cells up to 4 km grid cell resolution. The third basin was chosen for its complex drainage networks and lowlying relief and due to difficulties in automated delineation of drainage networks.

Figure 3.5: Study Basins: Location of the Mackenzie River Basin, the Saskatchewan River Basin and The Snare River Basin. Source: Shaded relief image: USGS EROS Data Center, 1999.
3.6.1 South Saskatchewan River Basin

The South Saskatchewan River contains some of the largest rivers in the western Prairie Provinces and crosses three provinces, Alberta, Saskatchewan, Manitoba and one state, Montana. The basin ranges in elevation from approximately 260 m to 3550 m a.s.l. The South Saskatchewan River Basin (Figure 3.6) forms from seven small rivers flowing from the Great Divide in Montana and southern Alberta. The rivers merge, and form the South Saskatchewan at the junction of the Oldman, the Red and the Bow Rivers. The South Saskatchewan River then joins with the Red Deer River near the Alberta and Saskatchewan border.

Figure 3.6: HYDRO1K blue line network for the Saskatchewan River Basin (HYDRO1k 2001)
All basins originate in the Rocky Mountains in the west and flow eastward through the southern region of the Prairie Provinces where it joins with the North Saskatchewan River and forms the Saskatchewan River, which ultimately empties into Lake Winnipeg.

The combined drainage area of The North and South Saskatchewan River Basins are 336,000 km$^2$ of which 49 650 km$^2$ is the contributing area of The Red Deer sub-basin, 26 650 km$^2$ is from The Oldman River sub-basin, 25 500 km$^2$ is from The Bow River sub-basin and 19 375 km$^2$ is from The South Saskatchewan River sub-basin, approximately 40% of the drainage in The South Saskatchewan River Basin is through internal drainage such as sloughs due to the hummocky nature of the topography (Conly and Martz 1999). The basin includes prairie grasslands, agricultural lands as well as aspen parkland in the northeastern regions of the basin. (The Saskatchewan River Basin Story 2004).

Climates within the region vary. Banff, Alberta is located 1397 m a.s.l. in the Rocky Mountains with mean annual temperatures around 2.1 °C and average annual precipitation of 461.9 mm. Medicine Hat, Alberta, located at 717 m a.s.l., has a mean annual temperature of 5.5°C and average annual precipitation amounts of 329.1 mm. Saskatoon, Saskatchewan, has an elevation of 501 m a.s.l., with a mean annual temperature of 1.9°C and annual precipitation amounts of 362.7 mm. The Pas, Manitoba, at 271m a.s.l., exhibits mean annual temperatures of -0.4°C and average precipitation amounts of 436.1 mm (Figure 3.7).

The monthly discharge at the Saskatoon, SK station ranges between 28 and 1920 m$^3$/s in extreme event years with a mean discharge of 263 m$^3$/s (Figure 3.8) with a basin area of approximately 121,000 km$^2$. Minimum discharges are consistently found between December and March while maximum discharges are found in the spring and early summer months between April and July. Between August and December, discharges begin to consistently decrease. The discharge curve shows two distinct peak discharge events, one in May and one again in
Figure 3.7: Climographs for selected locations in the Saskatchewan River drainage basin. Source: World Climate Data, 2001. Data Period: 1942-1990

June. The first event indicates the spring snowmelt runoff period. The second event in June represents summer runoff from melt water associated with mountain snow pack melt water as well as glacial melt water inputs (Conly and Martz 1998). Since the introduction of Gardiner River Dam, flows have been somewhat effected and as a result flow tend to be slightly increased in the winter than and slightly decreased in the summer compared to pre-dam conditions (Conly and Martz 1998).
3.6.2 The Mackenzie River Drainage Basin

The Mackenzie Basin is a substantial basin that extends over 1,787,000 km² and is ranked 10th in contributing area and 15th in the world for mean annual discharge. The Mackenzie River drains almost 20% of the Canadian land base and is the fourth largest river in North America. The elevation ranges from 0 m a.s.l. to approximately 3,400 m a.s.l. in the southern regions (Figure 3.9). The Mackenzie River flows through the northwestern portion of Canada and drains into the Beaufort Sea. The Mackenzie Basin consists of six sub-basins, the Athabasca, Peace, Great Slave, Liard, Great Bear, and Peel; three major lakes, Athabasca, Great Slave, and Great Bear, and three deltas, Peace-Athabasca, Slave River and Mackenzie deltas (Krause 1996). Physiographic regions represented in the basin are the Arctic Coastal Plain, the Precambrian Shield, the Western Cordillera, and the Interior Plain (Krause, 1996).

The basin contains a number of land cover types. Coniferous forest is the largest portion (35%), followed by mixed wood (19%), transitional forest (19%), arctic and alpine tundra (7%), lakes and rivers (7%), deciduous forest (6%), and
agricultural lands (2%) in the southern regions (Krause 1996). Major forest types present include sub-arctic spruce, pine, birch and larch forest.

The Mackenzie Basin has a wide range of climates (Figure 3.10). Inuvik, found on the Arctic Coastal Plains at 68 m a.s.l, has a mean annual temperature of $-9.2^\circ$ C and annual precipitation amounts of 255.6 mm. Yellowknife, located on the Precambrian Shield at an elevation of 205 m a.s.l. has a mean annual temperature of $-5.1^\circ$ C and annual precipitation amounts of 259.5 mm.
Whitehorse, at 703 m a.s.l. in the Western Cordilleran range, has a -0.7°C mean annual temperature and 263.8 mm of annual precipitation. Fort McMurray, in the Interior Plains at an elevation of 369 m a.s.l. has a mean annual temperature of -0.2°C and annual precipitation amounts of 443.1 mm.

Figure 3.10: Climographs for selected locations in the Mackenzie River drainage basin. Source: World Climate Data, 2001. Data Period: 1942-1990

The monthly mean discharge of the Mackenzie River at the Arctic Red River station ranges between 2,129 and 27,703 m³/s in extreme event years, with a mean discharge of 9,119 m³/s (Figure 3.11) and a basin area of approximately 1,787,000 km². Minimum discharges occur in the spring months between December and April while maximum discharges are found in the summer and fall.
months between May and November. Largest discharge peak events consistently occur in June.

Figure 3.11: Mean Monthly discharge hydrograph for the Mackenzie River Drainage basin at the Arctic Red River Station. Source Data: Water Systems Analysis Group (WSAG 2002). Data period: 1972-1992

3.6.3 Snare River Drainage Basin

The Snare River Basin is composed of 13 main sub-basins ranging from 13.5 to 4,708 km² and has a total basin area of 15,733 km² (Figure 3.12). The Snare River Basin is located in the Taiga Shield physiographic region of Canada, and is a contributing basin to the Mackenzie River Basin. Plant species found in this region include coniferous species such as jack pine and black spruce as well as paper birch and trembling aspen. The geology of the area is Canadian Shield with rock outcroppings. The Taiga Shield also has areas of permafrost and short cool growing seasons. The soil is acidic and organic in nature.

The Snare River basin is a small basin with climates similar to those seen at Yellowknife as the basin is close to Yellowknife. Climate information taken from Cangrid data set (Figure 3.13) shows the mean annual temperature to be approximately 0.1°C and annual precipitation amounts to be 298.7 mm. The Yellowknife station (Figure 3.9) shows mean annual temperatures of −5.1°C and annual precipitation amounts of 259.5 mm.
Figure 3.12: The Snare River Basin and study area, 100 m-grid cell resolution and blue line network (Environment Canada, 2004)


The monthly discharge at the Ghost Lake Station ranges between 18 m³/s and 147 m³/s in extreme event years with a mean discharge of 60 m³/s (Figure 3.13) and
has a basin area of approximately 1,631 km². The total Snare River drainage basin has an area of approximately 15,733 km². Decreasing river discharges are consistently found between October and March while maximum discharges are found in the spring and early summer months between April and August. Between August and December, discharges begin to decrease.


3.7 Study Site Summary

The basins chosen for this study have been selected for a number of reasons: (1) Availability of data: due to time and budgetary constraints, publicly available data used by the scientific community such as government supplied DEMs and blue line vector data was essential in undertaking this study. (2) Varying basin size and DEM resolution: to allow for a comparison across a number of different basins and commonly used DEM resolutions to provide for an evaluation of upper and lower limits of the DEM correction procedure. (3) Physiographic variability of the basins: each basin has a number of physiographic regions and a diverse landscape exhibiting very different topographic relief from prairie lowlands to rugged mountain regions. (4) Evaluate algorithm: for enforcing drainage while re-scaling grid cell resolution in very complex terrain.
CHAPTER 4
Results and Discussion

4.1 Parameters and Basin and Network Delineation for Each Basin

Descriptive statistics are given in the following sections for each of the basins. The original HYDRO1k DEM, DEMs developed using the alternative approach and those created using ANUDEM have all been examined. For the purpose of comparison, blue line network properties taken from the National Atlas of Canada are used as a reference for comparing the drainage networks and basins obtained for each DEM developed.

4.2 the Saskatchewan River Basin – Descriptive Statistics

Initial evaluation of the different model output includes a simple description of the input and output datasets and an initial z-test (two sample means test) on the mean values of the resulting DEM populations. Table 4.1 presents some of the descriptive statistics for the Saskatchewan River Basin. A general decreasing elevation value trend can be seen using the different buffer widths, where the original mean elevation is 1650 m and the resulting ANUDEM mean elevation being 1603 m. The different buffer widths provide mean elevations between these two values. Table 4.2 presents the output from a z-test analysis on the sample means. There is a significant difference between the original HYDRO1k DEM mean elevation and the mean elevation derived from ANUDEM processing on this
Table 4.1: Descriptive Statistics for the Saskatchewan River Basin

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
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<td>1603</td>
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<td>1647</td>
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<td>Median Elevation (m)</td>
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<td>1642.5</td>
<td>1640.5</td>
<td>1648.5</td>
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<td>Standard Deviation</td>
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<td>732.324</td>
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<td>Kurtosis</td>
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<td>-1.192</td>
<td>-1.131</td>
<td>-1.130</td>
<td>-1.140</td>
<td>-1.156</td>
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</tr>
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<td>Skewness</td>
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<td>0.006</td>
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<td>0.041</td>
<td>0.036</td>
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<td>Minimum Elevation (m)</td>
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<td>4126587</td>
<td>4113895</td>
<td>4158325</td>
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Table 4.2: Z-Test for two sample means: Each DEM compared to original Saskatchewan River Basin (1km resolution) for analysis

<table>
<thead>
<tr>
<th></th>
<th>SkDEM - Original Sask Basin DEM</th>
<th>ANUDEM - Enforced Drainage</th>
<th>DEM - Using 1 Cell buffer width</th>
<th>DEM - Using 3 Cell buffer width</th>
<th>DEM - Using 5 Cell buffer width</th>
<th>DEM - Using 10 Cell buffer width</th>
<th>DEM - Using 20 Cell buffer width</th>
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<tr>
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<td>1647</td>
<td>1644</td>
<td>1651</td>
<td>1642</td>
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<td>Known Variance</td>
<td>531517</td>
<td>491965</td>
<td>536432</td>
<td>534724</td>
<td>531775</td>
<td>536298</td>
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<td>Observations</td>
<td>2496</td>
<td>2425</td>
<td>2509</td>
<td>2506</td>
<td>2502</td>
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<td>2501</td>
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<td>z</td>
<td>2.322</td>
<td>0.080</td>
<td>0.163</td>
<td>0.281</td>
<td>-0.067</td>
<td>0.386</td>
<td></td>
</tr>
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<td>P(Z&lt;=z) two-tail</td>
<td>0.020</td>
<td>0.936</td>
<td>0.871</td>
<td>0.778</td>
<td>0.946</td>
<td>0.699</td>
<td></td>
</tr>
<tr>
<td>z Critical two-tail</td>
<td>1.960</td>
<td>1.960</td>
<td>1.960</td>
<td>1.960</td>
<td>1.960</td>
<td>1.960</td>
<td>1.960</td>
</tr>
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</table>
DEM. Similarly varying degrees of difference can be found when examining each buffer width for effects on the mean elevation of the DEM.

Analysis of the elevation difference grids (Figure 4.1) reinforces the decrease in overall elevation values. The maximum elevations changes can also be seen to decrease across the different processes, and it is evident that the overall effect of the buffer is maintained to the buffer region. The main decrease occurring in the ANUDEM processed DEM, with varying degrees of effect found with each of the buffer widths. Table 4.1 similarly presents changes in the DEM character of the various buffer widths as well as the original and ANUDEM processed DEMs.

4.2.1 The Saskatchewan River Basin - HYDRO1K DEM Analysis, Without Drainage Enforcement

The original DEM provided by the HYDR01K dataset sets the stage for DEM analysis. Descriptive statistics presented in Table 4.1, indicate the maximum and minimum elevations at 2391 m and 3548 m a.s.l., respectively. The mean value is 1650 m and elevations have a range of 3157 m. Changes in the descriptive statistics will be compared to this data set as this is the presently accepted DEM and in an attempt to preserve this DEM as much as possible it is important to establish a level standard level of values.

In Table 4.2 the original Saskatchewan River Basin DEM has a kurtosis of -1.127 and exhibits as skewness factor of 0.043 (Table 4.1). Since this is the standard elevation class make up, all analysis will be compared to these values. The kurtosis and skew describe the general distribution of the data sources and also highlights the effect the high elevation values have on the overall DEM character. There are relatively few high elevation values in this drainage basin and a large number of low elevations, thus minor changes in the high elevation values may have significant impacts on the general character of the DEM, mainly the mean elevation value and the make-up of the elevation classes.
Figure 4.1: Differences in elevation value following different procedures of drainage enforcement original Saskatchewan River Basin DEM vs ANUDEM (Figure A), original Saskatchewan River Basin DEM vs 3 cell buffer width DEM (Figure B) and ANUDEM vs 3 cell buffer width DEM.
4.2.2 The Saskatchewan River Basin - Drainage Enforcement Using ANUDEM

As a result of using ANUDEM drainage enforcement algorithm several drastic changes to the DEM occur. The most prominent occurs in the maximum value category. The maximum elevation changes from 3548 m a.s.l. in the original data set to a maximum of 2915 m a.s.l., the minimum value also decreases by 1m. Due to the change in the range the mean value decreases by 47 m as well we see a decrease in standard deviation to.

Also exhibited in this data set is the extreme shift in the skewness, which decreases to a value 0.006 from 0.043 seen in the original data set. As indicated previously in the descriptive statistics a large decrease occurs in the maximum elevation category and produces changes in the kurtosis and skewness values.

A z-test for the difference of mean is used to evaluate the effect the different processes have on the overall mean of the basin DEMs. The null hypothesis is that there is no difference in the means between all the different drainage enforcement procedures. The initial analysis of ANUDEM as a drainage enforcement provides a z score that is larger than the critical value at the 0.05 critical level for a two-tailed test. This finding rejects the null hypothesis and states there is a significant difference in the means of the ANUDEM output DEM and the original Saskatchewan River Basin DEM. This is important as it emphasizes the overall changes in the DEM resulting from this level of drainage enforcement and denotes the general smoothing of the DEM in the higher elevations.

4.2.3 The Saskatchewan River Basin - Buffer Width of 1 Cell

Following the first model run, using a 1 cell buffer width, descriptive statistics were found to be comparable to the original data set. The mean values for the elevations found in the study area decrease by 2 m to 1648 m a.s.l., similarly the median value has decreased by 1 m to 1644 m and the range has not changed. The
maximum elevation values has also held constant in the first set of model data as what was initially found for the input data set, suggesting that there has been little to no effect on the surrounding DEM, maintaining the initial research question of effectively correcting the hydrological flow of the DEM while maintaining little effect on values deemed "correct" in the DEM outside the stream line boundaries.

The kurtosis and skewness values calculated for this DEM indicates very minor changes from the initial set of data, Table 4.1. These values represent a miniscule shift to a slightly lower mean elevation value (1648 m), resulting from a very small shift in the number of overall values found in the maximum elevation group. While the maximum elevation value is not changed, there are few elevation values in the higher elevation classes that are subsequently reduced in value due to the ANUDEM processing algorithm. This is expected since drainage paths are known to be incorrect and elevation values must be altered to preserve the blue line drainage. However, there is a significant difference between this data set and the output of the ANUDEM enforcement algorithm on the DEM without any buffering effect.

At the 1 cell buffer model run an examination of the mean values using the z-test indicates that the two-tailed test indicate there is no significant difference between the mean values of the DEMs, and fails to reject the null hypothesis. This supports the statement that there is little effect on the DEM outside the drainage buffer area and that effects on the DEM are localized to the 1 cell buffer region.

4.2.4 The Saskatchewan River Basin – Buffer Width of 3 Cells

Using a buffer of 3 cells, the output results are similar to the characteristics of the input DEM, and those exhibited in the 1 cell buffer results (Table 4.1). Again as with the first model run, the minimum, maximum, mean, standard deviation, and range all remain constant to the values identified in the original DEM, enforcing the second objective of the thesis statement.
Also in the generated elevation difference grids, Figure 4.1, show effects of the
drainage enforcement process are limited to the area within the buffer region.
Thus, the generation of a hydrologically accurate DEM, without a substantial
change to DEM characteristics, has been achieved. The kurtosis suggests a very
small shift to a more platykurtic distribution; however, this is a very small change.

Deviations from the ANUDEM output have changed significantly, effectively
displaying the ability to minimize the effect of ANUDEM on the surrounding
DEM values that are not a portion of the drainage network, and localizing the
effect of drainage enforcement to the buffered region.

Using a buffer width of 3 cell, like in the 1 cell buffer model run, the two-tailed
test results fail to reject the null hypothesis and there is no significant difference
between this DEM and the original DEM (Table 4.2). As with the 1 cell buffer
width, this supports the assumption that there is no initial evidence of large scale
changes to the DEM characteristics, especially the mean and range of values, with
this level of hydrography integration.

4.2.5 The Saskatchewan River Basin - Buffer Width of 5 Cells

Using a buffer width of 5 cells, the output results are again very similar to the
characteristics of the input DEM, and those exhibited in the 1 and 3 cell model
runs (Table 4.1). As with the first model run, the minimum, maximum, and range
all remain constant to the values identified in the original DEM; however,
differences are being generated in the median and mean of the data set. These
values are quite small, however, and deemed unimportant as the mean and median
change by 6 and 5 m respectively.

Characteristics for the 5 cell buffer width model run (Figure 4.1) indicate no shift
in class characteristics, a slight change in kurtosis and skew suggest there is a
small shift in elevation classes toward a slightly more platykurtic distribution.
Examination of z-scores for a comparison of the significance between the means of the 5 cell buffer model run and the initial input DEM, indicates again there is no significant difference between the 5 cell results an the original DEM, and we fail to reject the null hypothesis, suggesting there is no significant difference between these two population means (Table 4.2).

4.2.6 The Saskatchewan River Basin - Buffer Width of 10 Cells

The 10 cell buffer output results are again very similar to the characteristics of the input DEM, and those exhibited in the 1, 3, and 5 cell model runs, Table 4.1. The minimum, maximum, and range all remain constant to the values identified in the original DEM unlike the 1 – 5 cell buffer widths, the mean elevation increases by 1 m to 1651 m, similarly there is a small increase of 3.0 m in the median elevation. There is also a small change in the standard deviation at this level in the model run, which changes from 729 to 731. The overall trend in this output is somewhat different than in the previous 5 sets of model outputs, where we see a slight increase again in values from those values present in the 5 cell descriptive statistics. Histogram values for skew and kurtosis show a gradually larger shift towards a more platykurtic distribution, however, as in the previous model runs, this is a very small shift.

A z-test analysis for the DEM generated using a 10 cell buffer again fails to reject the null hypothesis and there is no significant difference between the two DEMs with a two- tailed test at the 0.05 critical level (Table 4.2). The 10 cell buffer width has no significant difference between the original DEM and this DEM. There has been no significant change in the overall elevation values at this level in the model run.

4.2.7 The Saskatchewan River Basin - Buffer Width of 20 Cells

A 20 cell buffer width begins to differ from the characteristics of the input DEM, and those exhibited in the 1, 3, 5, and 10 cell model runs (Table 4.1). The most
significant change occurs in the maximum elevation that decreases from 3548 m a.s.l. observed in the original data and the four preceding buffer widths to 3425 m, a difference of 123 m. The minimum, and range remain relatively close to the values identified in the original DEM. Differences are observed in the median and mean of the data set. The mean decreases by 8.0 m from the original DEM and the median decreases by 4.5 m. A change in the standard deviation at in the model run is also observed with a decrease from 729 to 724.

The 20 cell buffer width (Table 4.1) shows a slight change in kurtosis to -1.16 from -1.12, in the original DEM. This indicates a change in the nature of the distribution to an even more platykurtic distribution. The shift in these values represents the smoothing effect ANUDEM has on higher elevation values as the buffer width increases.

A z-test of the means of using a 20 cell buffer smoothing algorithm again fails to reject the null hypothesis and there is no significant difference between the two populations (Table 4.2), however, there has been smoothing and the maximum elevation has decreased by a magnitude of 123 m and a decrease in the elevation range and a decrease in the total number of unique elevation values present in the new DEM.

4.2.8 The Saskatchewan River Basin DEM – RMSE Evaluation

Root Mean-Square Error (RSME) is a type of generalized standard deviation. RMSE is usually calculated to determine the differences in two subgroups or effects between two models or variables.

The RMSE was calculated for the Saskatchewan River Basin DEM and the ANUDEM as well as the 3 cell buffer width DEM (Table 4.3). The lower the RMSE the better the model has performed, the RMSE value is highest for the Saskatchewan River Basin and ANUDEM comparison. The RMSE decreases as the Saskatchewan River Basin DEM is compared to the 3 cell buffer width DEM.
resulting from the alternative process. This supports the principle that the alternative process limits the effects of drainage enforcement on the original DEM and maintains original DEM characteristics.

<table>
<thead>
<tr>
<th>DEM Comparison</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKDEM and ANUDEM</td>
<td>35</td>
</tr>
<tr>
<td>SKDEM and 3 Cell Buffer DEM</td>
<td>16</td>
</tr>
</tbody>
</table>

**Table 4.3**: Root Mean Squared Error (RMSE) Calculation for difference between the Saskatchewan River Basin DEM and ANUDEM

### 4.3 the Saskatchewan River Basin DEM Drainage Network Characteristics

The following sections will examine the drainage network derived from each of the DEMs used in the study. The HYDCOR acronym is a naming convention used to indicate the hydrologically corrected DEM at the specific buffer width associated with the acronym, for example HYDCOR1, represents the hydrologically correct DEM using a 1 cell buffer width for DEM correction. The drainage networks derived by TOPAZ using the HYDCOR datasets will be compared to the “blue line” networks extracted from the National Atlas of Canada dataset at a scale of 1:7,500,000.

#### 4.3.1 The Saskatchewan River Basin - Blue-line and delineated networks

Initial visual analysis of the drainage networks indicates that all buffer width results provide a drainage network that is consistent with that from the National Atlas of Canada blue-line data set. Figure 4.2, displays the original HYDRO1k drainage network and its deviation from the correct drainage network. There are a number of inconsistencies, the main ones being in the headwaters of the North Saskatchewan River Basin and in the Lake Diefenbaker area in the southeastern portion of the drainage basin.
Figure 4.2: National Atlas of Canada blue line network and HYDRO1K derived blue line drainage network.

Figure 4.3 to Figure 4.5 display the TOPAZ delineated networks and drainage basin boundaries for each buffer width. All drainage networks appear to be consistent with the correct blue line data highlighted in Figure 4.2. The main difference is that some minor drainage networks previously unidentified in the National Atlas dataset are now delineated using the automated process.

4.3.2 The Saskatchewan River Basin – Elevation value grid analysis

Examination of the descriptive statistics for the Saskatchewan River Basin suggest DEM drainage enforcement by ANUDEM causes a general smoothing of higher elevations in the DEM. An initial comparison of grid elevations for a small area was performed and can be seen in Figure 4.6 to 4.12. This area is a portions of the headwaters of one of contributing channels to the Saskatchewan River, the area has
Figure 4.3: Drainage networks derived from TOPAZ on DEMs developed from the alternative procedure using 1 (Figure A) and 3 cell buffer widths (Figure B)
Figure 4.4: Drainage networks derived from TOPAZ on DEMs developed from the alternative procedure using 5 (Figure A) and 10 cell buffer widths (Figure B)
Figure 4.5: Drainage networks derived from TOPAZ on DEM developed from the alternative procedure using 20 cell buffer width

both high elevations that are smoothed but outside the scope of the stream channel as well as high elevations that need to be “cut” by ANUDEM in order to properly place the drainage system as deemed correct by the National Atlas of Canada blue line hydrography (Geogratis 2000).

Figure 4.6 represents the original Saskatchewan River Basin elevation data. This is data taken directly from the HYDRO1k dataset and is deemed to be hydrologically correct by the USGS (HYDRO1k, 2001). Note the lowest elevation values highlighted in red, which indicate a developing drainage channel. Two areas worth noting are highlighted in this set of elevation data. The first is highlighted in yellow, and this area represents a high elevation area along this drainage channel. The second area is highlighted in orange, and represents another area of higher elevation that is at a reasonable distance from the channel. This area can be directly compared to Figure 4.7, which represents the ANUDEM enforced elevation values. The area of yellow has been smoothed out and the channel
location has been modified based on blue line hydrography influence in ANUDEM. This elevation “editing” is acceptable as it is acknowledged that the original DEM was incorrect in this area and the channel is now in the proper location. A quick survey of the elevation grid shows that all elevation values in this example have been modified in some form. Similarly, the orange highlighted area shows significant elevation smoothing that is performed by ANUDEM. Figure 4.7 compares two drainage networks; the first in red indicates the channel as defined in the HYDRO1k Saskatchewan River Basin and the new drainage network, in blue, developed ANUDEM processing on the HYDRO1k DEM. Areas of green indicate overlapping sections that occur between the two drainage networks.

In Figure 4.7, the area highlighted by orange has had some smoothing performed by ANUDEM. This would seen as unnecessary smoothing of elevations, as it is unnecessary to edit the entire original DEM to correctly incorporate the ANUDEM influence. The HYDRO1k dataset has been previously deemed as hydrologically correct and over-processing may inadvertently remove elevation features from the DEM that are unwanted. The general smoothing of the topography is reflected in the descriptive statistics (Table 4.1) and the z-test for two means (Table 4.2).

Using a one cell buffer width (Figure 4.8), the results are somewhat different from what would be found in the ANUDEM processed elevation grid. The one cell buffer width effectively limits ANUDEM influence to one grid cell resolution width along the channel. The one cell buffer appears to be too narrow for this resolution and hydrography scale. The new process because is only one grid cell wide does not offer any influence on the incorrectly placed drainage networks present in the original HYDRO1k dataset. It has been identified that many of the inconsistencies in the
**Figure 4.6:** SKDEM raster elevation value grid. Red represents stream channel. Orange indicates area of high elevation and yellow indicates area of high elevation along channel.
Figure 4.7: ANUDEM enforced raster elevation value grid. Blue represents stream channel. Orange indicates area of high elevation and yellow indicates area of high elevation along channel. Red indicates stream channel present in original SKDEM elevation matrix.
![Figure 4.8: 1 cell buffer width enforced raster elevation value grid. Blue represents stream channel. Orange indicates area of high elevation that does not require high elevation smoothing. Yellow indicates area of high elevation along channel that requires elevation smoothing](image-url)
Figure 4.9: 3 cell buffer width enforced raster elevation value grid. Blue represents stream channel. Orange indicates area of high elevation that does not require high elevation smoothing. Yellow indicates area of high elevation along channel that requires elevation smoothing.
Figure 4.10: 5 cell buffer width enforced raster elevation value grid. Blue represents stream channel. Orange indicates area of high elevation that does not require high elevation smoothing. Yellow indicates area of high elevation along channel that requires elevation smoothing.
Figure 4.11: 10 cell buffer width enforced raster elevation value grid. Blue represents stream channel. Orange indicates area of high elevation that does not require high elevation smoothing. Yellow indicates area of high elevation along channel that requires elevation smoothing.
Figure 4.12: 20 cell buffer width enforced raster elevation value grid. Blue represents stream channel. Orange indicates area of high elevation that does not require high elevation smoothing. Yellow indicates area of high elevation along channel that requires elevation smoothing.
HYDRO1k DEM are at least 2 to 3 grid cells apart and a 1 cell buffer width is inadequate in resolving these problems. Also in some cases the blue line hydrography is not as long as the developed channel in the DEM, therefore as the blue line channel ends the buffer does not override the old pre-existing channel and the new channel and old channel merge towards the headwaters of this small contributing stream, in effect merging a new channel with incorrect headwaters. A wider buffer width will account for this error. Also it is important to note that the high elevation highlighted by orange is not effected by ANUDEM and is consistent with the original elevation values.

The three cell buffer width produces excellent results (Figure 4.9). The higher elevation errors highlighted in orange remain consistent with the elevations in the original HYDRO1k DEM and no un-necessary smoothing occurs, similarly the effects the in yellow highlighted areas indicate necessary elevation editing. The three cell buffer width also helps to eliminate a “drop” in the elevation values along the southern edge of the channel as produced in the 1 cell buffer and provides a more modest smoothing into the original HYDRO1k DEM. The effects of this buffer width are low as it allows a modest influence on the original DEM and minimizes the ANUDEM influence while preserving the ANUDEM developed drainage network, in areas where this influence is appropriate.

Using a five cell buffer width (Figure 4.10) provides similar results to those found using a three cell buffer width. The area of influence is approximately the width of five grid cell resolutions and allows for a more modest smoothing into the original DEM. Using this buffer width, the effects of pre-existing lower drainage channels are reduced but due to the nature of the algorithm still exist to some degree. The percentage weighting effectively reduces the pre-existing channels effect on the DEM as long as they are contained within the buffer region. This buffer width appears to be the limit in maximum size for this grid resolution (1 km) and hydrography scale (1:7,500,000). This buffer width still allows
preservation of the higher elevation areas as well as eliminates the effect that was apparent in ANUDEM enforcement on the entire DEM.

The ten and twenty grid cell buffer widths (Figure 4.11 and Figure 4.12) allows for the preservation of the ANUDEM developed channel and again effectively reduces pre-existing channel influence. These buffer widths also provide a very smooth transition into the original DEM; however, higher areas of elevation are beginning to be effected to do proximity to other drainage channels. Using a twenty-grid cell buffer width effectively includes all the grid cells in the elevation matrix into the processing stage. This not only dramatically increases processing requirements but also allows for ANUDEM influence once again over most of the DEM surface. Statistics in Table 4.1 and 4.2 also show the shift in statistics to suggest over-influence on the original DEM.

To summarize these results, the best buffer widths to use for this method of hydrological correction are either the three or five grid cell buffer widths. Statistics tend to show that the influence on the original HYDRO1k DEM is reduced using the three cell buffer width, however, visual examination of the smoothing process suggests that the five-cell process is better. Neither the three-cell buffer nor the five-cell buffer significantly alters the DEM structure.

4.4 The Mackenzie River Basin – Descriptive Statistics

Initial re-scaling issues (Armstrong 2003) show deviations of the drainage networks when linear aggregation is applied to DEMs with a resolution of 1 km aggregated up to 2 km. The drainage enforcement procedure has been performed on the Mackenzie River Basin, in an attempt to maintain the correct drainage networks at all grid resolutions greater than 1km, resulting from aggregation. Table 4.4 and Table 4.5 as well as Figure 4.13 show the changes that the Mackenzie River Basin DEM incurred as a result of enforcement using the
procedures described. Developed drainage networks using TOPAZ delineation on the corrected DEM can be seen in Figure 4.14 to Figure 4.16.

The overall trend in the mean elevation value shows a slight decrease, however, this decrease is quite small as compared to the resultant changes from ANUDEM enforcement alone. Similarly, the histograms present information that suggest that there again is as general "smoothing" of higher elevation values, thus effecting the distribution of the overall DEM elevation classes.

4.4.1 The Mackenzie River Basin - Analysis Without Drainage Enforcement

Original DEM characteristics for the Mackenzie River Basin (Table 4.4) at a resolution of 2km have a mean elevation value of 1339 m a.s.l., and median elevation of 1330 m a.s.l.. The maximum elevation is 3349m and minimum elevation is 11 m a.s.l. Standard deviation is 778.74 while the kurtosis and skew values are -1.065 and 0.082 respectively.

4.4.2 The Mackenzie River Basin - Drainage Enforcement Using ANUDEM

Following drainage enforcement there is a change in the overall DEM statistics (Table 4.4). The mean elevation decreases by 37 m and the median elevation similarly decreases by 36 m. The minimum elevation 11m remains constant, however, the maximum elevation decreases by 209 m. The standard deviation decreases to 754.82 as well as the kurtosis and skew factors decreasing to -1.094 and 0.065 respectively. This change in the kurtosis and skew are expected as it reflects the change in the maximum elevation and represents more of a platykurtic distribution or a distribution with more lower elevation values than found in the original DEM.

A z-test for means is used to evaluate the changes in the DEM mean values, the null hypothesis is that there is no difference between the means of the DEMs following drainage enforcement procedures. An examination of the z-test scores
### Table 4.4: Descriptive statistics for the Mackenzie River Basin

<table>
<thead>
<tr>
<th>Descriptive Statistics</th>
<th>MackDEM – 2 km Mack Basin DEM</th>
<th>ANUDEM - Enforced drainage</th>
<th>DEM - Using 1 cell buffer width</th>
<th>DEM - Using 3 cell buffer width</th>
<th>DEM - Using 5 cell buffer width</th>
<th>DEM - Using 10 cell buffer width</th>
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<tr>
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<td>1327</td>
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<td>Median Elevation (m)</td>
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<td>1329.5</td>
<td>1318.5</td>
<td>1314.5</td>
<td>1298</td>
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<td>Standard Deviation</td>
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<td>754.816</td>
<td>777.960</td>
<td>770.207</td>
<td>768.593</td>
<td>760.019</td>
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<td>Kurtosis</td>
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<td>-1.099</td>
<td>-1.069</td>
<td>-1.083</td>
<td>-1.080</td>
<td>-1.062</td>
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<td>Skewness</td>
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<td>0.065</td>
<td>0.079</td>
<td>0.072</td>
<td>0.073</td>
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<td>11</td>
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<td>Maximum Elevation (m)</td>
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<td>Sum</td>
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### Table 4.5: Z-test for two sample means: Each DEM compared to original Mackenzie River Basin DEM (2 km resolution)

<table>
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<tr>
<th>z-test: Two sample for means</th>
<th>mackDEM - Original Mack Basin DEM</th>
<th>ANUDEM - Enforced drainage</th>
<th>DEM - Using 1 cell buffer width</th>
<th>DEM - Using 3 cell buffer width</th>
<th>DEM - Using 5 cell buffer width</th>
<th>DEM - Using 10 cell buffer width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Elevation (m)</td>
<td>1339</td>
<td>1301</td>
<td>1338</td>
<td>1326</td>
<td>1323</td>
<td>1307</td>
</tr>
<tr>
<td>Known Variance</td>
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<td>569747</td>
<td>605221</td>
<td>593218</td>
<td>590734</td>
<td>577628</td>
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<tr>
<td>Observations</td>
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<td>2567</td>
<td>2638</td>
<td>2616</td>
<td>2610</td>
<td>2575</td>
</tr>
<tr>
<td>z</td>
<td>1.766</td>
<td>0.034</td>
<td>0.582</td>
<td>0.721</td>
<td>1.508</td>
<td>1.008</td>
</tr>
<tr>
<td>P(Z&lt;=z) two-tail</td>
<td>0.077337352</td>
<td>0.972274341</td>
<td>0.560062442</td>
<td>0.47046561</td>
<td>0.131</td>
<td></td>
</tr>
<tr>
<td>z Critical two-tail</td>
<td>1.959</td>
<td>1.959</td>
<td>1.959</td>
<td>1.959</td>
<td>1.959</td>
<td>1.959</td>
</tr>
</tbody>
</table>
between the means of the original 2km DEM and the ANUDEM enforced DEM rejects the null hypothesis and shows there is a significant difference between the two DEMs with a two-tailed test at the 0.05 critical level. Unlike the Saskatchewan River Basin the effects are slightly less on this DEM, due to the effects aggregation has already had on the DEM.

The difference grid (Figure 4.13) provides a visual representation of the overall effect ANUDEM has on the DEM and the widespread editing of elevation values.

**4.4.3 The Mackenzie River Basin - Buffer Width of 1 Cell**

General statistics for the basin following implementation of the 1 cell buffer are consistent with the original DEM statistics (Table 4.4). The mean elevations decrease by 1 m as well the median decreases by 0.5 m. The maximum elevation and range is also consistent with the original DEM. The standard deviation decreases to 777.96 from 778.74. Kurtosis and skew also shift again to -1.069 and 0.079 respectively.

Evaluation of the z-test for means using a 1 cell buffer width fails to reject the null hypothesis and states there is no significant difference (Table 4.5) between the DEM following the implementation of a 1 cell buffer width with a two tailed test at the 0.05 critical level.

Similar results are found in the DEM following processing using the 3 cell buffer smoothing algorithm as were found following implementation of a 1 cell buffer (Table 4.4). The mean elevation slightly decreases to 1327 m, a decrease of 12 m while the median elevation also decreases by 12 m to 1318 m. The standard deviation decreases to 770.21 while the kurtosis and skew of -1.083 and 0.072 have slight decreases but by very little amounts. It is important that the maximum
Figure 4.13: Differences in elevation value following different procedures of drainage enforcement on the Mackenzie River Basin DEM (2 km) vs ANUDEM (Figure A), the Mackenzie River Basin DEM (2 km) vs 3 cell buffer width DEM (Figure B) and ANUDEM vs 3 cell buffer width DEM.
elevation remains consistent with the maximum elevation found in the original DEM at the 2 km resolution.

4.4.4 The Mackenzie River Basin – Buffer Width of 3 Cells

The z-test (Table 4.5) for the 3 cell width buffer fails to reject the null hypothesis and reflects that there is no significant difference between the original DEM and the DEM resulting from using the 3 cell buffer width with a two tailed test at a critical level of 0.05. The elevation difference grid (Figure 4.13) also show the limited effect the new method has on the overall DEM characteristics outside of the buffer region.

4.4.5 The Mackenzie River Basin - Buffer Width of 5 Cells

Following implementation of the 5 cell buffer the mean elevation decreases by 15 m and the median elevation of the DEM similarly decreases by 15 m (Table 4.4). The maximum elevation and range both remain consistent with the original DEM. The standard deviation similarly decreases but the kurtosis and skew shows a slight increase compared to the kurtosis and skew in the 3 cell buffer width results. The overall statistics resemble the 3 cell buffer results with very slight, almost immeasurable differences.

A z-test for difference in means between the 5 cell buffer width and the original DEM (Table 4.5), again fails to reject the null hypothesis and shows there is no significant difference between the two DEMs with two tailed test at the 0.05 critical level. The z-scores also resemble the z-scores that are available for the 3 cell buffer width.

4.4.6 The Mackenzie River Basin - Buffer Width of 10 Cells

The DEM following processing using a 10 cell buffer width shows a decrease in the mean elevation to 1307 m a decrease of 32 m, the median also decreases by 32 m. This is the single largest change in DEM mean and median and
approaches the mean and median values observed following ANUDEM drainage enforcement on the original DEM. The standard deviation decreases to 760.02 nearing the ANUDEM standard deviation of 754.816. Different trends are noticed in the kurtosis and skew, however, and a slight increase is found to occur in these two values. The maximum, minimum and range of elevation values remain the same as they are in the original DEM.

Z-test scores between the 10 cell buffer width results and the original DEM fail to reject the null hypothesis and show there is no significant difference between the two DEMs. It is found that the z-scores are decreasing suggesting a the DEM characteristics move away from the original DEM and beginning to hold some similar DEM changes consistent with the ANUDEM enforced DEM.

4.4.7 The Mackenzie River Basin – RMSE Evaluation

Evaluation of the RMSE for the Mackenzie River Basin (Table 4.6), show results consistent with the descriptive statistics calculated for this DEM. Comparison of the Mackenzie River Basin DEM at the 2 km resolution and the ANUDEM processed DEM show higher RMSE values than the RMSE value from the 3 cell buffer width DEM. The decrease in RMSE value shows that the new method of drainage enforcement limits the effect that ANUDEM has on the DEM and allows for hydrological correction, while minimizing the effects the process has on DEM characteristics.

<table>
<thead>
<tr>
<th>DEM Comparison</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MACKDEM and ANUDEM</td>
<td>42</td>
</tr>
<tr>
<td>MACKDEM and 3 Cell Buffer DEM</td>
<td>34</td>
</tr>
</tbody>
</table>

Table 4.6: Root Mean Squared Error (RMSE) Calculation for difference between the Mackenzie River Basin DEM and ANUDEM
4.5 The Mackenzie River Basin – DEM drainage network characteristics

Figure 4.14 displays the difference in the drainage networks derived from TOPAZ using a 2km resolution DEM. The National Atlas blue-line data and the TOPAZ drainage network deviate significantly at this resolution. Similarly, the basin boundary also tends to decrease in size when automated techniques are used to delineate this boundary at this grid resolution.

Following the implementation of the one-grid cell buffer width process drainage networks were corrected when compared to the drainage network in the original blue-line data set. Similarly the basin boundary delineated following this process was also consistent with the drainage basin boundary delineated at the 1km grid cell resolution for this same DEM. The 3, 5 and 10-cell buffer also provide consistent results when looking at basin boundary and stream network development. Armstrong (2002) found that as basin resolution increased there tended to be a decrease in basin boundary and channel length. Similarly at the 2km grid resolution drainage networks began to change spatially. The of using the different buffer width allows for correction of the automated drainage networks while maintaining the basin boundary for each of the buffer widths, despite the change in grid cell resolution.

One noticeable difference between the National Atlas blue-line data and the TOPAZ delineated networks occurs in the lake areas. When assigning flow vectors for lakes for input into the ANUDEM portion of the procedure, flow vectors along each of edge of the lakes were assigned to allow for flow to the outlet. This is difficult to model and as a result, TOPAZ has delineated drainage networks along the lake boundary to the outlet points in each of the larger lakes. The result essentially removes the lake and develops two “rivers” along the lake boundary. While this is deemed incorrect in these lake areas, TOPAZ does
provide drainage networks that are correct for the rest of the DEMs processed by the alternative method.

Figure 4.14: The Mackenzie River Basin blue line network and basin boundary from the National Atlas of Canada and TOPAZ generated network generated on 2km resolution DEM

4.5.2 The Mackenzie River Basin – Elevation Value Grid Analysis

Initial examination of the Mackenzie River Basin drainage network at a grid resolution of 2 km shows some significant deviations in stream channel location. Figure 4.17 to Figure 4.21 shows the location of stream channels using TOPAZ corrects the drainage network according to the National Atlas of Canada blue-line
Figure 4.15: Drainage networks derived from TOPAZ on DEMs derived from the alternative process using 1 cell (Figure A) and 3 cell (Figure B) buffer widths
Figure 4.16: Drainage networks derived from TOPAZ on DEMs derived from the alternative process using 5 and 10 cell buffer widths
delineated networks. Initial treatment of the DEM using ANUDEM enforcement information (Geogratis 2000). However, it still processes areas of higher elevation that are outside the channel areas. Similar results can be found to those in the Saskatchewan River Basin elevations.

As with the Saskatchewan River Basin study area, the 1 cell buffer width appears to be too narrow for proper results. The descriptive statistics suggest that this buffer width provides the least effect on the DEMs characteristics; however, examination of the elevation grid suggests that one-grid cell is too narrow and does not eliminate a second flow path. In this trial it is important to note that the grid resolution is 2 km and that 1 grid cell resolution is a 2 km buffer whereas in the Saskatchewan River Basin, the grid cell resolution is 1 km. The 3 and 5 grid cell buffer widths provide better results when examining the elevation grids. The descriptive statistics show that there is no significant difference between these DEMs and the original DEM, although, the DEM characteristics are beginning to shift away from the original data source. The 3 and 5 grid cell buffer provides a modest smoothing into the original DEM and minimizes ANUDEMs effects on the outer regions of the elevation model.

The 10 grid cell buffer width again begins to allow for an over-influence of ANUDEM outside the effective stream network area (Figure 4.22). Higher elevation areas are being effected due to stream densities in the area.

The 10 grid cell buffer is effectively the same as the 20 grid cell buffer in the Saskatchewan River Basin, and the elevation value effect, coupled with the descriptive statistics suggest that the 10 grid cell buffer width is the maximum limit of a buffer width for this grid cell resolution.

In this example the process corrects the drainage network and allows a mechanism to minimize ANUDEMs effect on the original DEM. Descriptive statistics and z-test results show that ANUDEM influence on the Mackenzie River Basin with a
Figure 4.17: Mackenzie River Basin DEM raster elevation value grid. Red represents HYDROLk stream channel.
Figure 4.18: Mackenzie River Basin DEM after ANUDEM drainage enforcement. Red indicates HYDRO1k stream channel, Blue indicates ANUDEM enforced drainage channel, and Green indicates common channel cells.
Figure 4.19: Mackenzie River Basin DEM, using a 1 cell buffer width to control ANUDEM drainage enforcement. Blue indicates stream channel following drainage enforcement.

Figure 4.20: Mackenzie River Basin DEM, using a 3 cell buffer width to control ANUDEM drainage enforcement. Blue indicates stream channel following drainage enforcement.
Figure 4.21: Mackenzie River Basin DEM, using a 5 cell buffer width to control ANUDEM drainage enforcement. Blue indicates stream channel following drainage enforcement.
Figure 4.22: Mackenzie River Basin DEM, using a 10 cell buffer width to control ANUDEM drainage enforcement. Blue indicates stream channel following drainage enforcement.
two-kilometer grid cell resolution is less than the effect it has on the Saskatchewan River Basin DEM. Armstrong (2002) has previously shown that the DEM values in the aggregated DEM have changes and as a result the effect of ANUDEM on this altered DEM is less drastic as it is on the Saskatchewan River Basin DEM. Following the analysis, it is recommended that a buffer width of 3 grid cells is the ideal buffer width to use for a grid resolution of this magnitude, effectively smoothing the ANUDEM influence over six-kilometers of physical space.

4.6 The Mackenzie River Basin – 4 km Grid Cell Resolution

The procedure was also performed on the Mackenzie River Basin DEM at a grid cell resolution of 4 km. The results provided drainage basin correction in some areas of the DEM, however, overall consistency between the blue line data and the automated delineation procedure was not found. Armstrong (2003) found substantial differences in the drainage basin networks when linear aggregation was performed at the 4km cell resolution level, as well basin characteristics also changes. These changes were un-correctable using this proposed method of drainage enforcement despite some minor corrections occurring in the basin DEM. The procedure appears to reach a maximum limit of 4 km grid cell resolution where a single grid cell is larger than the magnitude of the largest river valley.

4.7 The Snare River Basin – Descriptive Statistics

Examination of the descriptive statistics (Table 4.7) shows that the mean elevation of the original DEM is 450 m a.s.l. and the mean elevation using ANUDEM and each of the different buffer widths provide mean elevations of 449.5 m a.s.l. Similarly, all statistics show common properties between the ANUDEM and each buffer width, which are very slightly different from the original DEM. The most important attribute, the maximum elevation, remains constant throughout all DEMs, and the minimum also only decreases by 1 m a.s.l. It is suspected that the change in the mean elevation is due to this small change in
minimum elevation value. The standard deviation, kurtosis and skew all remain within hundredths of the original values found in the original DEM.

Similar finding are recognized in the z-test for means, Table 4.8. The z-tests fails to reject the null hypothesis that there is no difference between the means of the different DEMs following the methods of drainage enforcement at the 0.05 critical level with a two-tailed test, despite ANUDEM influence the DEMs remain the same. This is due to the very low landscape present in the are and the inability to effectively process the landscape without removing all the topographic relief in this small DEM. Similarly the high density of drainage networks with complex and divergent flow also make DEM correction problematic for ANUDEM.

4.8 The Snare River Basin DEM drainage characteristics

TOPAZ drainage delineation following processing (Figure 4.23) provides drainage networks that are not consistent with the blue-line network for the basin, however general drainage trends are maintained. The general trend of moving water to the South West is common between the two networks. The TOPAZ network (highlighted in red in Figure 4.26) does not model the lake and lowlands very accurately. The statistics presented in Section 4.6 show a modest change in elevation, a mere change of 100 m of elevation this small change is problematic as the entire DEM will be classified as a low area, and the high abundance of small lakes and low spots create an endless number of depressions. TOPAZ processing will perform depression filling and the flat area algorithm and in essence provide the drainage network identified below, which is inaccurate, despite any modest changes that ANUDEM or the alternative procedure can perform on the DEM surface.

DEMs with drainage characteristics such as these will provide the lowest limit in ANUDEM and the alternative procedure in terms hydrological correction, similarly this type of landscape also presents a limitation of TOPAZ to model such low relief, highly complex drainage areas.
Figure 4.23: Snare River Basin drainage network from TOPAZ (red) and blue line data (Blue) following processing using a 3 cell buffer width

4.9 Summary

Results for the various drainage basin DEMs provide useful information regarding an alternative method of drainage enforcement. The proposed procedure outlines the upper limits in grid cell resolution as well as the limits in topographic variability and drainage complexity. The procedure provides results that maintain the original basin characteristics and do not adversely effect the DEM especially with respect to changes in higher elevation areas. The hydrological integrity of the “blue line” drainage networks are maintained while allowing for some alteration of the DEM to maintain these networks. The general
### Table 4.7: Descriptive statistics for The Snare River Basin

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</table>

### Table 4.8: Z-test for two sample means: Each DEM compared to original Snare River Basin DEM (30m resolution) for analysis

<table>
<thead>
<tr>
<th>z-test: Two Sample for means</th>
<th>SnareDEM - Original Snare River Basin DEM</th>
<th>ANUDEM - Enforced drainage</th>
<th>DEM - Using 1-cell buffer width</th>
<th>DEM - Using 3-cell buffer width</th>
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<td>449.5</td>
<td>449.5</td>
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<tr>
<td>Known Variance</td>
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<td>1.960</td>
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<td>1.960</td>
<td>1.960</td>
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basin DEM characteristics are also maintained outside the buffered areas, maintaining the DEM integrity in areas where alterations are undesirable. The procedure in particular maintains the general elevation composition, and effects on maximum elevation that are found using ANUDEM alone are eliminated.

The procedure provides modelers with several choices for data input as well as several choices to use on buffer widths depending on their grid cell resolution. The results for three and five cell buffer widths are excellent; as well the 1 and 10 cell buffer widths are also acceptable and can be used for very small resolution grid cells or for the larger grid cell resolutions depending on the users desire.
CHAPTER 5

Conclusions

The availability of Government offered DEMs and hydrography information has provided modelers with an excellent resource for the purpose of landscape evaluation. The availability of GIS and new GIS tools for the processing of these different data types provides the advantage of speed, efficiency, reproducibility and decreased costs; however, the data provided must be accurate enough to provide meaningful results. Data offered by the USGS, such as the HYDRO1k dataset, has been used for several years, and even though it is deemed hydrologically correct, it possesses several elevation and hydrographical errors. On a global scale, these errors may seem minor; however, for more localized studies these errors can be detrimental to hydrological modeling. Automated delineation processes will provide incorrect results based on these errors. The effects will include error in basin size, and shape, network development and topographic variables such as slope and aspect.

The initial study using the Saskatchewan River Basin found that the hydrography layer was relatively accurate except in areas of very low relief. The HYDRO1k DEM provided drainage networks that appear to follow Pleistocene drainage networks, thus having a serious impact on modeling the southern regions of the basin. Similarly, these errors were noted in some low relief areas existing between the North and South Saskatchewan River networks, effectively allowing
large-scale “stream piracy” between the two rivers. Using ANUDEM, a widely accepted DEM correction procedure, corrected the drainage problems; however, the processing fundamentally changed the nature of the DEM, especially reducing the higher elevations in the DEM. The new procedure developed for this study provided a method that limits ANUDEM influence to the stream network area while taking advantage of its ability to correct for the proper blue line drainage in areas where it was needed. The buffer widths that best suited this DEM with a resolution of 1 km and a hydrography scale of 1:7,500,000 were the 3 and the 5 cell buffer widths. Combined this with the knowledge achieved from the higher resolution DEM of the Mackenzie River Basin, it would be best to propose using the 5 grid cell buffer width, as this provides approximately 5 km of smoothing.

Results using the Mackenzie River Basin are somewhat different from the Saskatchewan River Basin results. Armstrong (2002) found that increasing the grid cell resolution provided differences in drainage channel length and drainage basin boundary and size beginning at the 2 km grid cell resolution. This has implications on slope and gradient, which in turn affects physical properties such as flow velocity and soil moisture storage. Slope is very severely affected by the averaging effect of aggregation, and that the smoothing effect of increasing the spatial scale effects the higher areas of elevation the greatest. Similarly, using ANUDEM also has an effect on smoothing the higher elevations of a DEM. The procedure proposed, at the 3 grid cell buffer width, allows for ANUDEM influence again along the drainage network alone and does cause the higher area effects already identified in increasing grid resolutions. The process, does correct for basin boundary area and drainage network delineation errors that are a result from the processing of the aggregated DEM using TOPAZ. The best buffer used for this purpose is the 3 grid cell buffer, which at resolution of 2 km translates into 6 km of physical distance for smoothing. The buffer width also appears to reach its upper limits where the valley width approaches the grid resolution. This is similar to Armstrong’s (2002) results where grid scale poses problems when scale reaches valley widths. The process appears to be at its maximum limit at
this resolution as increasing resolution past this point provided results that were not consistent with the original DEM at any buffer width or at any level. Some basin characteristics have been found to change using the proposed procedure; however, these are not as pronounced as the changes caused by ANUDEM, an accepted DEM correction procedure. Minor changes in the DEM are expected, due to the processing of the DEM in the buffer areas, small changes will still equate to small changes in the general statistics of the DEM.

The Snare River Basin processing provided disappointing results. The processing of this basin using ANUDEM initially did not cause significant deviations from the original DEM. This is due to the relative flatness of the DEM and the very low relief present in the area. The drainage network is also very complex and exhibits divergent flow as well as chaotic drainage patterns. The blue line data for this area provides many lakes and very short drainage networks connecting these small water bodies. Using buffers of 1, 3, 5, 10 and 20 grid cells did not provide successful results. This is partly due to the complex drainage networks and the density. Due to the density, the buffer widths even at the 1 grid cell width were very close and in most cases overlapping, and thus the smoothing process could not function properly. This type of drainage network provides the uppermost limit in terms of hydrography scale and density. TOPAZ also appears to reach its limit in this type of landscape. The depression filling and flat area algorithm tend to fill the landscape and provide improper drainage networks for this level of hydrographic detail.

This study has presented a procedure to enforce drainage on existing DEM without reverting to “stream-burning” processes, by building on and improving a commonly used program for DEM development. The study identifies some of the errors in publicly held data sets as well as highlights some of the DEM changes that occur prior to processing using ANUDEM. The process has provided a mechanism by which DEM correction can be implemented for different grid resolutions and hydrographic scales, in order to maintain proper drainage networks and drainage basin parameters.
General guidelines can be established for use of the different buffer width based on drainage density and grid resolution. For both the Saskatchewan River Basin and the Mackenzie River Basin best results for drainage networks at a 1:7,500,000 scale was determined to be 5 and 6 km respectively. Therefore, buffer widths should be used to correspond to grid cell resolutions to approximate these physical distances. Similarly, for DEMs with smaller grid resolution a wider buffer width can be used to approximate these physical distances to provide the best results.

5.1 Future Research Considerations

Further studies on implementing drainage correction procedures should continue to focus on varying grid resolution and hydrographic scale, and basins of varying size and topographic relief. Methods to develop better stream channel morphology than can be obtained using ANUDEM should be explored and applied to this process. Survey and hydraulic model terrain data (Tate et al. 2002) should be evaluated to see how it can be employed by this process. Procedures, which can preserve relief when re-generating existing DEM using ANUDEM should also be examined. For example, perhaps all grid cells with a zero-CSA value can be used as ridge “hard break lines”.

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