INTEGRATING DRAINAGE ENFORCEMENT INTO EXISTING RASTER DIGITAL ELEVATION MODELS AND THE DEVELOPMENT OF THE HYDROLOGICAL DRAINAGE BASINS OF THE MANNING DIVERSIFIED FOREST PRODUCTS LTD FOREST MANAGEMENT AREA

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PROGRESS REPORT AND FINAL REPORT

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1.0 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 (DEMs) 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).

2.0 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).

2.1 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).

2.2 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.

2.3 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 2000). 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).

2.4 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 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 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.

3.0 Methodology

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.

Following utilization of the procedure on the approved drainage basins for the study a subsequent analysis of a smaller drainage basin in the MDFP FMA management areas of P6 and P9 and forest management quota areas of P7 and P1 was employed. The study was conducted on a Government supplied DEM with a resolution of 25m X 25m. Due to processing issues with the shear volume of the data at this resolution, the grid resolution was aggregated to 100m X 100m resolution.

3.3 Data Sources

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).

4.0 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 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.

Table 4.1: Descriptive Statistics for the Saskatchewan River Basin

Descriptive Statistics	SkDEM - Original Sask Basin DEM	ANUDEM - Enforced Drainage	DEM - Using 1 Cell buffer width	DEM - Using 3 Cell buffer width	DEM - Using 5 Cell buffer width	DEM - Using 10 Cell buffer width	DEM - Using 20 Cell buffer width
Mean Elevation (m)	1650	1603	1648	1647	1644	1651	1642
Median Elevation (m)	1644.5	1602	1644	1642.5	1640.5	1648.5	1640
Standard Deviation	729.053	701.402	732.415	731.248	729.229	732.324	724.893
Kurtosis	-1.127	-1.192	-1.131	-1.130	-1.140	-1.156	-1.169
Skewness	0.043	0.006	0.042	0.041	0.036	0.027	0.019
Range	3157	2525	3158	3158	3158	3158	3035
Minimum Elevation (m)	391	390	390	390	390	390	390
Maximum Elevation (m)	3548	2915	3548	3548	3548	3548	3425
Sum	4118517	3886558	4135827	4126587	4113895	4158325	4106892

Table 4.2: Z-Test for two sample means: Each DEM compared to original Saskatchewan River Basin (1km resolution) for analysis

	SkDEM -Original Sask Basin DEM	ANUDEM - Enforced Drainage	DEM - Using 1 Cell buffer width	DEM - Using 3 Cell buffer width	DEM - Using 5 Cell buffer width	DEM - Using 10 Cell buffer width	DEM - Using 20 Cell buffer width
Mean	1650	1603	1648	1647	1644	1651	1642
Known Variance	531517	491965	536432	534724	531775	536298	526920
Observations	2496	2425	2509	2506	2502	2518	2501
z		2.322	0.080	0.163	0.281	-0.067	0.386
P(Z<=z) two-tail		0.020	0.936	0.871	0.778	0.946	0.699
z Critical two-tail		1.960	1.960	1.960	1.960	1.960	1.960

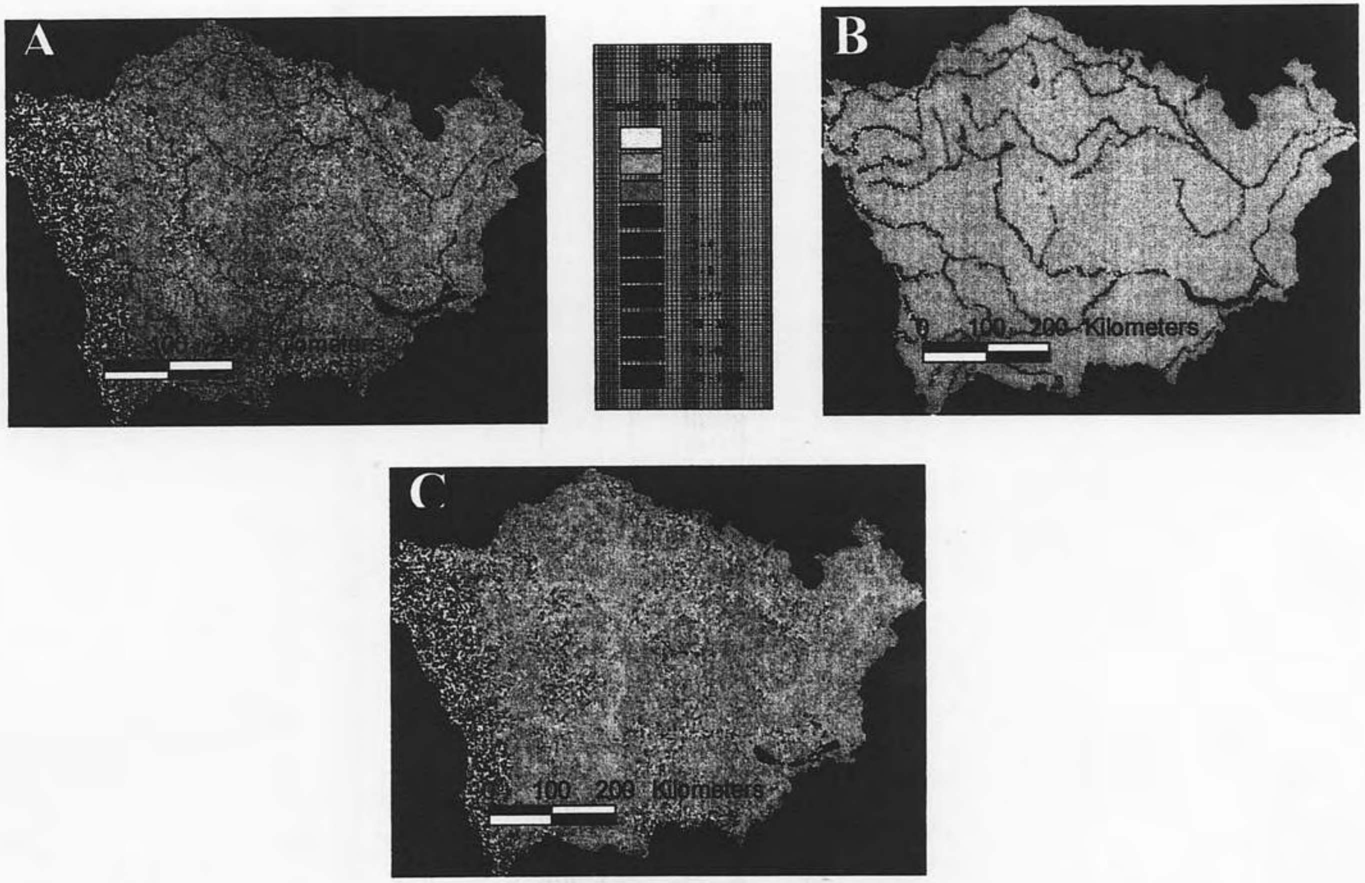

Figure 4.1: Differences in elevation value following different procedures of drainage enforcement original Saskatchewan River Basin DEM vs ANUDEM (Figure A), original Saskatchewan River Basin DEM vs 3 cell buffer width DEM (Figure B) and ANUDEM vs 3 cell buffer width DEM.

4.3 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 4.2 .

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 The Manning Diversified Forest Products Forest Management Area

Visual inspection was performed for t he MDFP FMA hydrological drainage basins. The overall drainage networks and drainage basins provided results that were very close with a few very minor imperfections on some of the first order streams. Figure 4.3 represents these drainage networks and the drainage basin resulting from the automated delineation of drainage system from the government supplied DEM.

Table 4.3: Descriptive statistics for the Mackenzie River Basin

Descriptive Statistics	MackDEM – 2 km Mack Basin DEM	ANUDEM - Enforced drainage	DEM - Using 1 cell buffer width	DEM - Using 3 cell buffer width	DEM - Using 5 cell buffer width	DEM - Using 10 cell buffer width
Mean Elevation (m)	1339	1302	1338	1327	1324	1307
Median Elevation (m)	1330	1294	1329.5	1318.5	1314.5	1298
Standard Deviation	778.735	754.816	777.960	770.207	768.593	760.019
Kurtosis	-1.065	-1.099	-1.069	-1.083	-1.080	-1.062
Skewness	0.082	0.065	0.079	0.072	0.073	0.083
Range	3338	3129	3338	3338	3338	3338
Minimum Elevation (m)	11	11	11	11	11	11
Maximum Elevation (m)	3349	3140	3349	3349	3349	3349
Sum	3534221	3341425	3530917	3470845	3455153	3365757

Table 4.4: Z-test for two sample means: Each DEM compared to original MackenzieRiver Basin DEM (2 km resolution)

z-test: Two sample for means	mackDEM - Original Mack Basin DEM	ANUDEM - Enforced drainage	DEM - Using 1 cell buffer width	DEM - Using 3 cell buffer width	DEM - Using 5 cell buffer width	DEM - Using 10 cell buffer width
Mean Elevation (m)	1339	1301	1338	1326	1323	1307
Known Variance	606428	569747	605221	593218	590734	577628
Observations	2639	2567	2638	2616	2610	2575
z		1.766	0.034	0.582	0.721	1.508
P(Z<=z) two-tail		0.077337352	0.972274341	0.560062442	0.47046561	0.131
z Critical two-tail		1.959	1.959	1.959	1.959	1.959

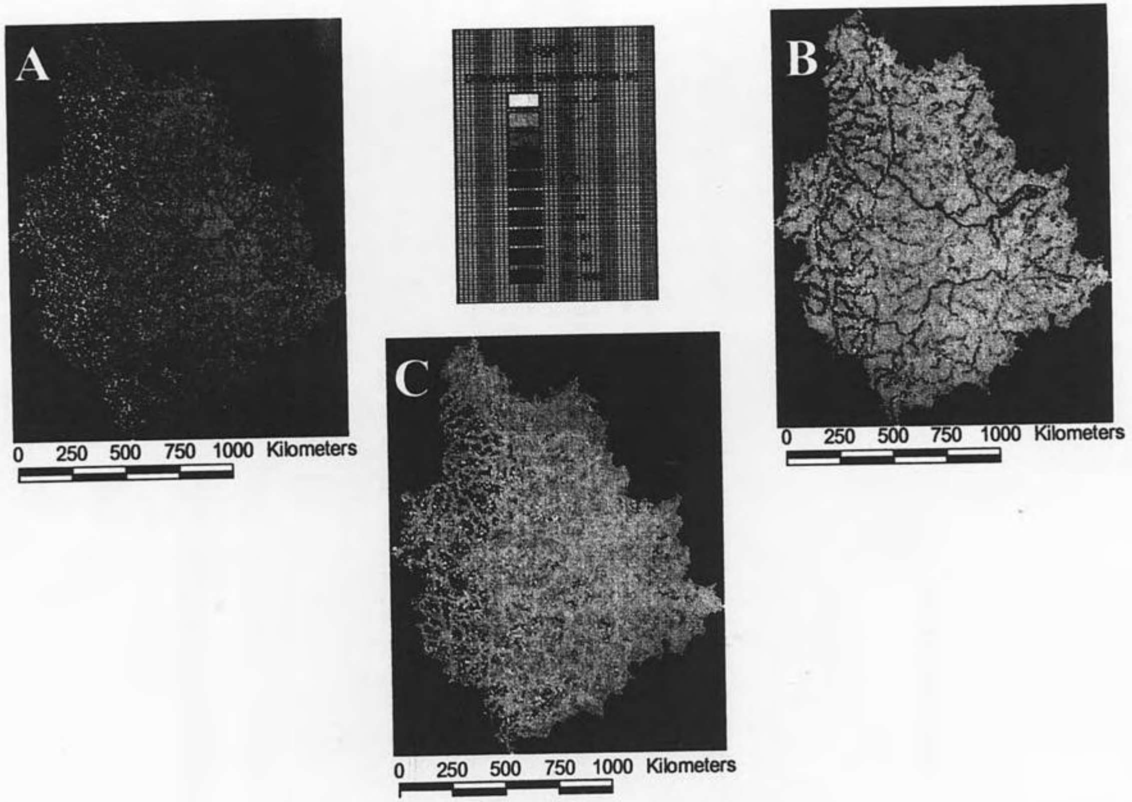

Figure 4.2: Differences in elevation value following different procedures of drainage enforcement on the Mackenzie River Basin DEM (2 km) vs ANUDEM (Figure A), the Mackenzie River Basin DEM (2 km) vs 3 cell buffer width DEM (Figure B) and ANUDEM vs 3 cell buffer width DEM.

Figure 4.3: Drainage network and DEM for the MDFP FMA as well as forest management units P7 and P10.

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 generalbasin 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.

5.0 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 pirating" 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. 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.

Results of the MDFP FMA hydrological unit model run provided a digital drainage network which was visually very consistent with known blue line information for the drainage area. Similarly basin delineation was quite accurate and did not possess any obvious drainage differences. Slight imperfections resulting from a DEM limited in the west part of the DEM was an effect of political boundaries and the lack of data past the Province of Alberta Boundary.

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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 nad 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.