Improving overland flow routing by incorporating ancillary road data into Digital Elevation Models

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Abstract

Roads, ditches, and culverts influence hydrological and geomorphological processes significantly. However, most hydrological models continue to rely solely on regional digital elevation models (DEMs) to derive overland flow directions even though these DEMs have been shown to contain inadequate topographical information to effectively represent linear landscape features. This paper introduces a methodology that improves the accuracy of grid-based overland flow routing through the use of ancillary road, ditch, and culvert data. The road enforcement algorithm (REA) that was developed re-routes overland flow on either side of a road independently, thereby enforcing linear landscape features within the flow direction matrix. The overland flow patterns resulting from the implementation of the REA differ significantly from flow patterns derived using conventional GIS routing algorithms. A test application in the prairies of southern Alberta, Canada shows the REA affects intra-watershed runoff transport as well as the size and shape of DEM-derived watersheds. The flow direction matrices created with the REA can be incorporated into any grid-based hydrological model.

Keywords: Watershed Delineation, Road, Geographic Information System (GIS), Flow Direction, Digital Elevation Model (DEM), Hydrological Modelling

1 Introduction

Digital elevation models (DEMs) are routinely used for hydrological applications because overland flow routing is controlled by topography (Moore et al., 1991). DEMs are used to delineate watersheds (Jensen and Domingue, 1988), analyze channel networks (Quinn and Beven, 1991; Tarboton, 1991), predict soil water content (Quinn and Beven, 1993; Quinn et al., 1995), predict erosion potential (De Roo and Jetten, 1999; Takken et al., 2001b, c, Ludwig et al., 1996), model non-point pollution (Cluis, et al., 1996), and carry out flood and hydrograph analysis (Oliveria and Maidment, 1999). However, Moore et al. (1991) also stated that the deficiency of many hydrological and water quality models is their inability to account for the effects of terrain on flow processes. The results from hydrological models are, therefore, often grossly simplified and unrealistic.

Linear landscape features can significantly affect the hydrological and geomorphological processes within a watershed. For example, tillage furrows as small as 2 cm in depth can significantly modify flow networks and erosion patterns (Ludwig et al., 1996; Souchere et al., 1998; Cerdan et al., 2001; Takken et al., 2001a; Souchere et al., 2003). Tague and Band (2001) showed that roads can also modify soil moisture conditions significantly. Studies conducted in the United States by Montgomery (1994) and in Ethiopia by Nyssen et al. (2002) concluded that roads concentrate runoff, significantly increasing the formation of gullies, as well as changing the size and shape of watersheds. In a study in the western cascades of Oregon, Wemple et al. (1996) reported a 21 to 50% increase in watershed drainage density as a result of roadside ditches and culverts. Similarly, Montgomery (1994) reported a 60% increase in drainage density following road construction. The consequence of extending the channel network is a more rapid delivery of runoff to streams, resulting in shorter times to peak flow and increased total discharges (Dijck, 2000; Jones et al., 2000; La Marche and Lettenmaier, 2001). A study by Dijck (2000) demonstrated that the density, continuity, and total length of the "between-field runoff network" (viz. ditches) are more influential on runoff hydrographs in agricultural areas of France than field properties (viz. levelling and surface roughness). When few drainage features (i.e., culverts) are present, roads can also cause substantial inter-basin water transfers (Luce and Wemple, 2001). Ludwig et al. (1996) and Dijck (2000) suggested that agricultural fields are frequently hydrologically isolated. Runoff that is generated from one field is seldom transferred to an adjacent field due to the presence of ditches at field edges. Watershed boundaries can, therefore, differ significantly from conventional DEM-derived watersheds (Ludwig et al., 1996).

Grid (or raster) matrices are the most common data structure for DEMs. The fundamental step of raster-based hydrological models is the assignment of flow directions based on DEM elevation values (Martz and Garbrecht, 1998). Although a number of flow direction algorithms exist (e.g., Quinn et al., 1991; Lea, 1992; Costa-Cabral and Burges, 1994; Tarboton, 1997; Orlandini et al., submitted manuscript), the deterministic eight neighbour (D8) flow direction algorithm introduced by O'Callaghan and Mark (1984) is the most commonly used and was implemented for this research. The D8 algorithm compares the elevation of each cell to its eight adjacent neighbours. A single flow direction is then assigned from each cell to the neighbouring cell in which the path of steepest descent exists. The subsequent flow direction matrix defines the connectivity of the landscape with respect to water, sediment, and contaminant transport.

However, hydrological models often do not account for the limitations of DEMs to accurately represent the landscape (Walker and Willgoose, 1999; Schneider, 2001). Inadequate elevation point sampling densities used to generate DEMs, and abrupt discontinuities in the landscape lead to the absence of linear landscape features (viz. roads and ditches) in DEMs (Gao, 1998; Walker and

Willgoose, 1999; Gong et al., 2000; Huang, 2000). Figure 1 illustrates the lack of road and ditch representation that frequently occurs in DEMs.
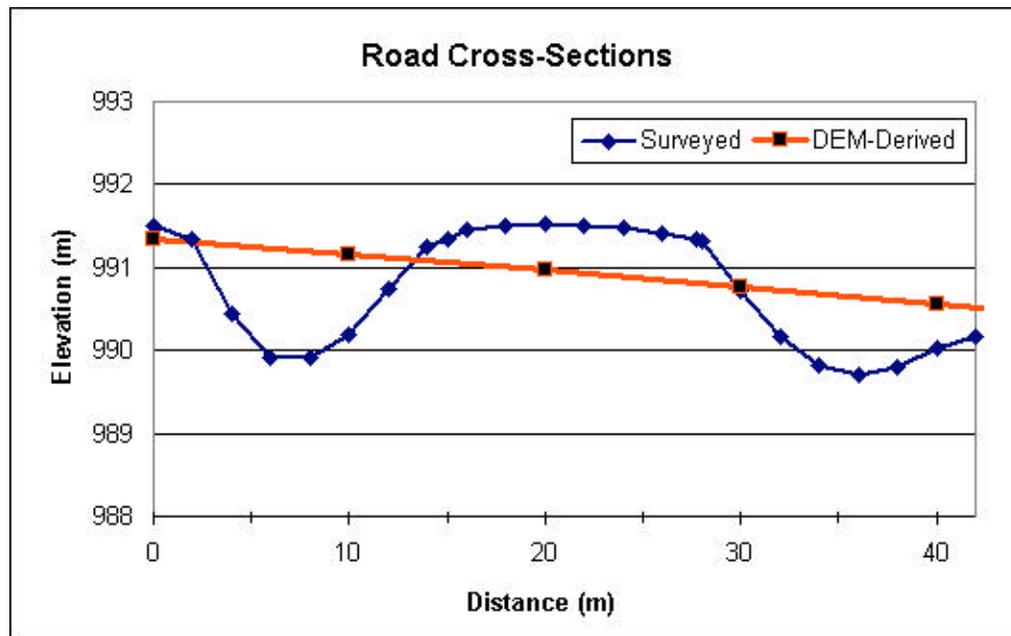
Figure 1. Road cross-section derived from a DEM interpolated using the TOPOGRID command within ArcInfo (See Results and Discussion) and surveyed using a theodolite.

Because artificial linear features are not represented in DEMs, flow direction matrices that are derived from DEMs alone are often inaccurate (Ludwig et al., 1995; Takken et al., 2001a, b, c). Schneider (2001) stated that although DEMs are suitable for many applications, users must be aware of the representation a DEM must possess for successful modelling applications. The ability of linear landscape features as small as tillage furrows to modify overland flow directions (Souchere, et al., 1998, Takken et al., 2001a, b, c) suggests the need to interpolate DEMs from point elevation densities at the scale of centimeters. Recognizing the limitations of current technology, hydrological modelers have begun to incorporate ancillary data when deriving flow directions from DEMs. Saunders (2000) utilized ancillary stream data to impose or "burn" stream vector data to improve the accuracy of flow direction matrices near streams. "Burning" streams refers to the process of decreasing the elevation of grid cells representing watercourses to enforce the known drainage patterns on the flow direction matrix. Takken et al. (2001c) developed the tillage-controlled runoff pattern (TCRP) algorithm that incorporates knowledge regarding tillage orientation into the Limburg Soil Erosion Model (LISEM). Similarly, this paper proposes a methodology to utilize ancillary road, ditch, and culvert data to account for linear landscape features in hydrological models. The need to develop an algorithm to incorporate ancillary road, ditch, and culvert data into existing grid based flow direction algorithms stemmed from:

- the observation that the location of roads frequently cannot be ascertained by examining DEM-derived channel networks,
- the effects linear landscape features impose on several biophysical processes within watersheds,
- the potential severity of consequences of inaccurate watershed delineations, for example, the movement of "contaminated" water across watershed boundaries (PFRA, 1983).

If cross-sectional attributes of roads were known, it may seem as though manipulating pre-existing DEMs accordingly would be an effective method to enforce the effects of artificial linear features on flow direction matrices. For instance, grid cells representing roads could be raised, and grid cells representing ditches could be lowered. However, conventional grid based routing procedures (e.g., D8) require the removal of closed depressions with a flooding algorithm (Martz and Garbrecht, 1998; Rieger, 1998), therefore, alterations made to the DEM prior to "filling" may be nullified. In fact, altering the DEM in this way would exacerbate the extent of flat areas (i.e., grid cells lacking a neighbour at a lesser elevation). Because flow directions within flat areas must be defined arbitrarily, the accurate modelling of runoff in these areas is impossible (Turcotte et al., 2001). Martz and Garbrecht (1998) suggested this as the single greatest weakness of conventional grid-based routing algorithms, and developed a flat area algorithm that produces more realistic results than the conventional D8 algorithm, although it remains dependent on arbitrary decision rules (Turcotte et al., 2001). The procedure described in the present study was developed to utilize DEM elevation values prior to the filling process. Although several authors have stated that depressions are spurious features created during the interpolation process of DEMs (e.g., Martz and Garbrecht, 1998; Rieger, 1998), depressions are actually common features in recently glaciated terrain (Mark, 1988). Additionally, the construction of roads has also created many artificial landscape depressions. The assignment of flow directions prior to filling is, therefore, an effective way to identify the lowest points, or thalwegs in the landscape. The procedure described herein simulates raising road elevations and lowering ditch elevations within the DEM to produce a manipulated flow direction matrix. With approximately 2.5 million km^2 of low-relief prairie grassland in North America (Figures 12 and 13) the REA is applicable in a significant portion on North America and many other parts of the world.

2 Methodology

2.1 Conceptual Model of Roads, Ditches, and Culverts

The extent to which hillslopes are linked to stream channels depends on the runoff pathway to the stream (Wemple et al., 1996). Ludwig et al. (1996) subdivided this relationship into runoff contributing areas (viz. fields) and the "runoff collector network". For this study, the runoff collector network is

comprised of linear depression features (viz. ditches) and areas adjacent and upslope to raised roads. The runoff collector network influences overland flow directions in three ways:

- elevated roads can form overland flow barriers and flow path sinks, thereby re-routing flow along their orientation on the upslope side of the road (Figure 2).

- roadside ditches can create flow path corridors and flow path sinks (Figure 3).

- roads with flat cross-sectional profiles do not influence overland flow directions and are, therefore, excluded from the runoff collector network (Figure 4).

Figure 2 (a). Elevated roads: A large pool of runoff accumulates on the upslope side of an elevated road after a rare prolonged precipitation event in June, 2002. The downslope side of the road (not shown) showed no signs of runoff accumulation.
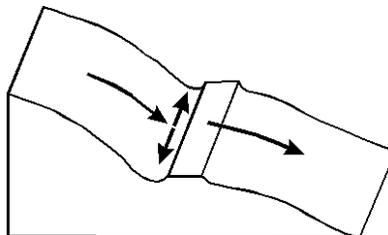
Figure 2 (b) Conceptual model of elevated road enforcement. Runoff is re-routed on the upslope side of the raised road, but is not affected on the downslope side of the road.

Figure 3 (a). Roadside ditches: Runoff changes its flow direction abruptly due to the presence of a road with ditches. The runoff in the picture is flowing from the field towards the road, at which point, the road imposes a ninety-degree change in direction. Thus, the roadside ditch enforces the progression of the runoff along the road perpendicular to the natural drainage pattern.
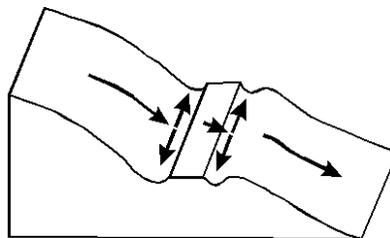
Figure 3 (b) Conceptual model of ditch runoff enforcement. Runoff is re-routed on both the upslope and downslope sides of the road.
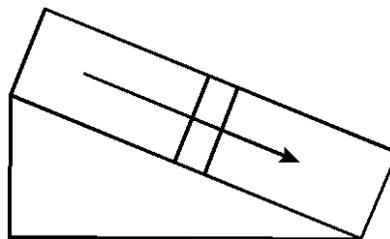
Figure 4. Flat cross-sectional road profiles: Conceptual model of runoff across a flat road. Runoff is not significantly affected by the road and continues to follow the topographic slope.

2.2 The Road Enforcement Algorithm

The algorithm described in this study was written in Microsoft Visual Basic, and is referred to as the road enforcement algorithm (REA). The REA is one of two algorithms that comprise the grid-based downscaling runoff model RIDEM (Rural Infrastructure Digital Elevation Model) (Duke et al., submitted manuscript). RIDEM is freely available from the authors upon request. The REA defines a

flow direction matrix for the cells adjacent to roads and imposes this matrix on the topographically derived (DEM) flow direction matrix. Thus, a single flow direction matrix is produced that accounts for roads, ditches, and culverts that can be used in any grid-based hydrological model.

The REA requires input files in ESRI ArcView / ArcInfo grid ascii format. The model requires a minimum of four input data layers including:

- a DEM (floating point),

- a topographically defined flow direction matrix,

- a topographically defined flow accumulation matrix,

- a road layer, and

- culvert locations (optional).

The REA model was created keeping in mind the restriction of data availability, therefore, the model contains three levels that enable the user to implement progressively more detailed road and ditch information.

2.2.1 REA Level I

The first level of the REA model is a single template model. Within the single template model a common cross-sectional template is assigned to all roads. This model requires the least amount of knowledge regarding the location and attributes of roads and ditches within an area. Road construction cross-sectional templates, as defined by government agencies (e.g., Alberta Transportation and Utilities, 1996), could be used to guide these assumptions. Within the conceptual view of roads described earlier, one of two cross-sectional road templates must be assigned to each road to enforce flow directions along its orientation, categorized as follows:

- a raised road template without adjacent ditches (i.e., an influence on the flow direction on the upslope side of the road only), or

- roads with adjacent ditches (i.e., an influence on the flow direction on both sides of the road).

If the road with adjacent ditches template is selected, the user must provide two values. The first value, referred to as the ditch-to-road height, defines the height of the road relative to the deepest part of the ditch (Figure 5). The second value, referred to as the ditch-to-field height, defines the depth of the ditch relative to the adjacent field (Figure 5). If the raised road without ditches template is selected, the ditch-to-road height is required, and the ditch-to-field height is effectively set to zero.

Figure 5. Road cross-section ditch-to-field and ditch-to-road heights.

2.2.2 REA Level II

The second level of the REA model is known as the variable template model. Within this model, segments of roads are classified into each cross-sectional category separately. The variable template model requires separate road input files for both the raised roads and roads with adjacent ditches categories. The model assumes a common cross-sectional template within each classification category. Thus, a single ditch-to-road height is required for each category. If the category road with ditches is included, the ditch-to-field height is also required.

2.2.3 REA Level III

The third level of the REA model is called the custom template model. This model is designed to remove the inherent road profile shape restrictions of the first and second level models. In contrast to the first and second level models that accept a single ditch-to-road and ditch-to-field height for each road category, the custom template model accepts separate data layers for the ditch-to-road and ditch-to-field heights for each grid point along the runoff collector network. The custom template model can, therefore, be used to assign spatially variable road cross-sectional templates within each classification category. Consequently, the custom template model permits detailed road cross-sectional profile data to be incorporated into the model from GPS or ground survey data. The third level provides two major benefits, including:

- the ability to represent road heights and ditch depths as continuous surfaces, and
- the modeled cross-sectional profiles on the left and right side of the road are independent.

2.3 Calculation of the Runoff Collector Network Flow Directions

Although slight variations of the REA exist depending on the model level selected, the logic of each procedure is identical (Figure 6).
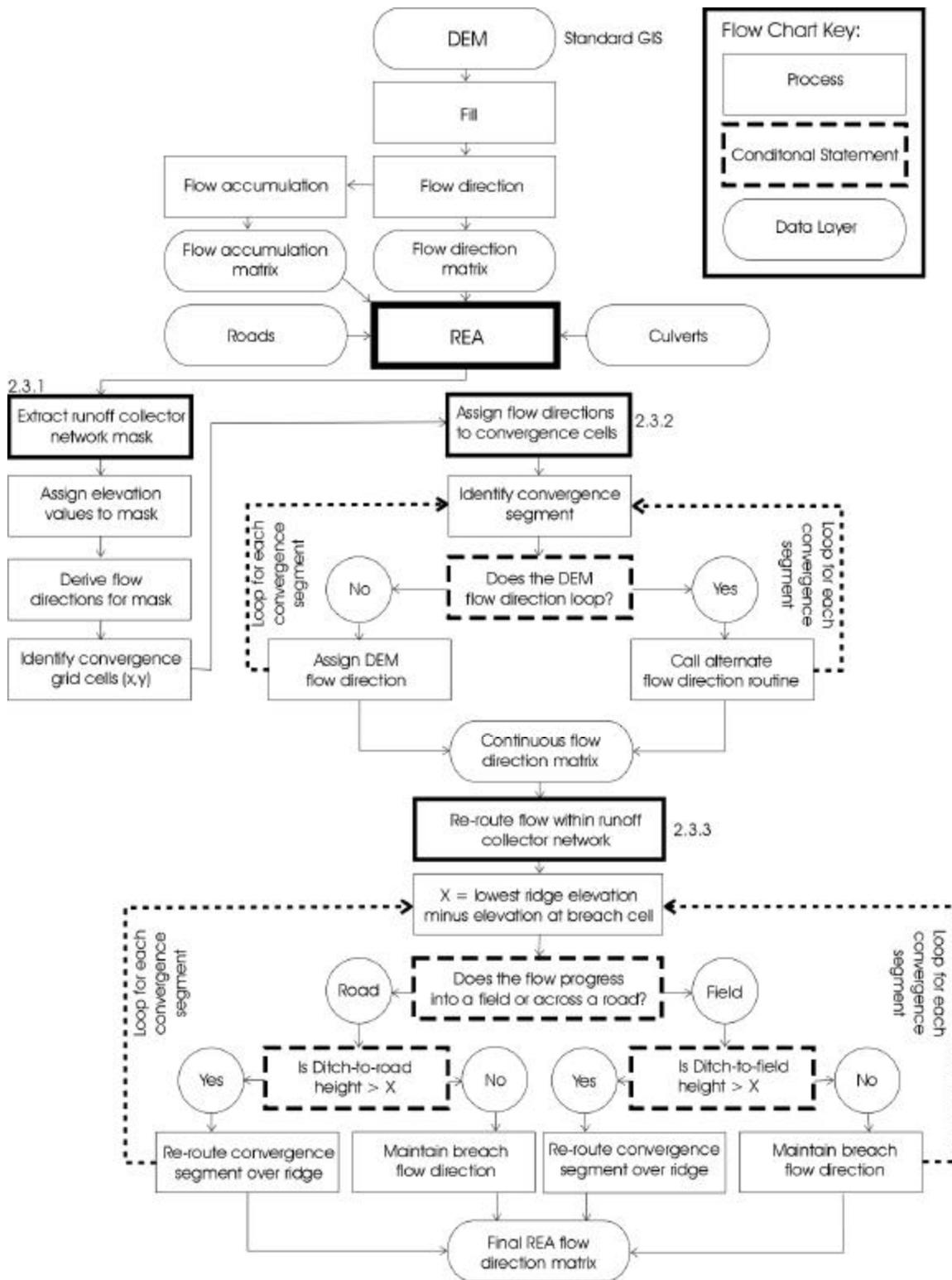
Figure 6. Simplified REA execution sequence flow chart.

2.3.1 Extract Runoff Collector Network Mask

The REA extracts grid cells adjacent to all road locations. Based on the cross-sectional attributes defined by the input parameters, the algorithm then identifies the runoff collector network as the grid cells adjacent to a road whose flow direction would be influenced by a linear landscape feature. This includes all ditch locations, and grid cells that flow across elevated roads within the topographic flow direction matrix. Depending upon whether culvert data are included, the algorithm then adds the grid cells representing culvert locations to the runoff collector network. Elevation values from the input DEM are then assigned to the runoff collector mask and flow directions are subsequently calculated using the conventional D8 approach (O'Callaghan and Mark, 1984). Grid cells of flow convergence that occur in the thalwegs (the lowest points in the landscape) of the runoff collector network are flagged as potential breach locations where runoff may exit the runoff collector network, either over a road or into a field. Convergence grid cells with a single inflow and outflow are considered spurious depressions, and are assigned a flow direction into their outflow grid cell (Figure 7).
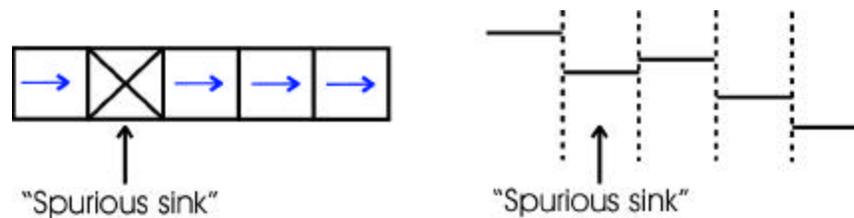
Figure 7. Spurious depression features.

2.3.2 Assign Flow Directions to Convergence Grid Cells

Convergence grid cells, analogous to the TCRP model incorporated in the soil erosion model LISEM (Takken et al. 2001b), are assigned the flow direction from the topographically defined flow direction matrix. A continuous runoff collector network is then created by assigning the topographically defined flow directions to the grid cells adjacent to the road locations that are not influenced by a linear landscape feature. Next, the flow direction matrix of the runoff collector network is superimposed on the DEM derived flow direction matrix. To ensure loops are not introduced to the flow direction matrix, the grid cells within the runoff collector network that are routed to each convergence site are identified. If the combined flow direction matrix loops back to the current convergence segment (i.e., the portion of the runoff collector network draining to the current breach grid cell), the algorithm assigns a flow direction to the grid cell on the opposite side of the runoff collector network. If this flow direction also creates a loop, the grid cell is flagged and the breach point is moved to the location within the convergence segment with the highest topographically defined flow accumulation value. At this stage the requirement to move convergence locations occurs exclusively in areas that were closed depressions in the DEM and would have been filled during the creation of the DEM-derived flow direction matrix. Following the completion of this step, a continuous flow direction matrix is

produced with the runoff collector network enforced and all convergence locations within the collector network identified.

2.3.3 Reroute Flow Within the Runoff Collector Network

In the previous step each convergence grid cell was assigned a flow direction to breach (or exit) the runoff collector network either across a road, or into an adjacent field. The depth of the runoff collector network relative to the adjacent road (or field), as defined in the DEM, determines whether runoff accumulates until a sufficient depth of water is attained to breach the runoff collector network, or overtop a ridge within the runoff collector network. For example, consider the two following scenarios of a road breach location with a ditch-to-road height of 1m (Figures 8a, b). If the elevation of the potential breach site is 100 m with two ridges within the runoff collector network at an elevation of 105 m and 110 m respectively, runoff would accumulate at the breach location until the runoff pool is 1 m deep. At that point runoff would breach the road (Figure 8a). However, if the elevation of the potential breach site is 100 m and the ridges within the convergence segment are 100.5 m and 110 m respectively, runoff would accumulate in the runoff collector network until the runoff pool is 0.5 m deep. At that point, runoff would breach the ridge within the runoff collector network, instead of breaching the road (Figure 8b).
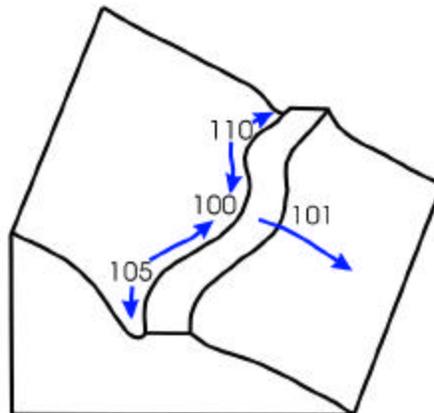
Figure 8 (a). Runoff patterns within the runoff collector network: Road breach scenario. Figure 8a shows the elevations of four key locations and the resulting drainage pattern. The runoff progresses from the two ridges in the runoff collector network towards the breach grid cell in the center. Runoff then flows from the depression on the upslope side of the road across the road and progresses downslope.
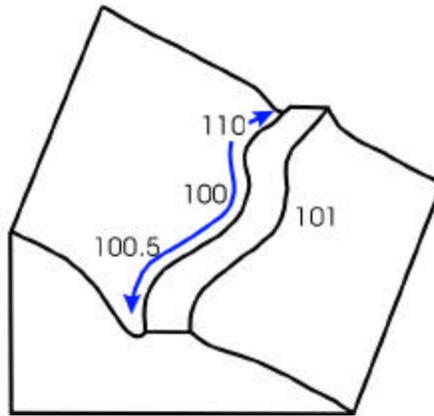
Figure 8 (b) Road height too large to enable breaching. Figure 8b shows the same scenario as Figure 8a, but with a different ridge top elevation. Due to the reduced height of the ridge located at the bottom of the figure, runoff no longer breaches the road. Instead the runoff continues to flow alongside the road perpendicular to the natural drainage pattern (hillslope direction).

To ensure flow within the runoff collector network cascades downslope the REA proceeds from the breach grid cell with the highest elevation to the breach grid cell with the lowest elevation. For each potential breach grid cell the convergence segment is once again identified. The algorithm retrieves the elevation and row and column coordinates of each ridge grid cell. If runoff has already been rerouted into the current convergence segment through a potential ridge, the grid cell is excluded as a potential ridge. Thus, flow is not rerouted over a potential ridge more than once, thereby ensuring the progression of runoff downslope. The elevation of each ridge identified in the convergence segment is subtracted from the elevation of the breach grid cell. If the difference is less than the height of water required to pool (i.e., the ditch-to-road or ditch-to-field height) and subsequently breach the runoff collector network then the entire convergence segment is rerouted through the lowest ridge grid cell. This process continues until a significantly deep convergence grid cell is located to facilitate a breach of the runoff collector network (Figure 9).
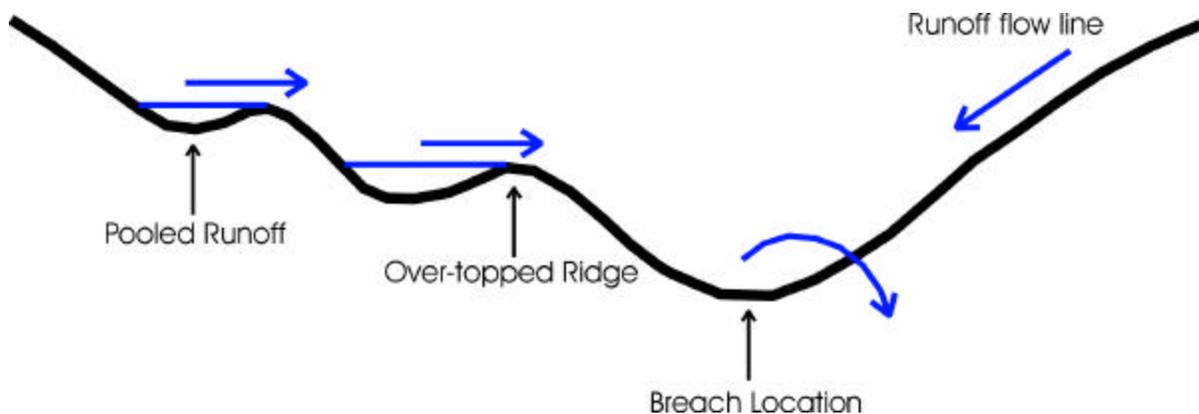
Figure 9.   Runoff collector network re-routing model.

2.3.3 Final Loop Check

In contrast to conventional flow direction algorithms that require the removal of closed depressions prior to flow path determination (Martz and Garbrecht, 1998), the REA utilizes the DEM in its original condition (i.e., prior to filling). This discrepancy can result in the creation of circular flow paths following re-routing. Therefore, the final step of the REA corrects these circular flow paths. To accomplish this task, the algorithm either restores the breach flow direction prior to re-routing within the runoff collector network, or moves the breach location to the grid cell with the highest DEM-derived flow accumulation value within the respective convergence segment.

3 Results and Discussion

The REA was tested in the south fork of the Piyami Drain watershed in southern Alberta, Canada. The south fork of Piyami Creek drains approximately 110 km^2 to the Oldman River. The topography is comprised of gently rolling hills near Piyami Creek, as well as extensive low-relief areas around the outer edges of the watershed. The total relief of the watershed is 204 m, with an average basin slope of 2.5%. The watershed contains approximately 202 km of gravel and paved roads. The results of implementing the REA were first presented at the field scale, followed by the results for the entire watershed. Field verification of the model was based on the following observations:

- culvert locations,
- road side cattails (*Typha latifolia*),
- runoff ponding,
- dead vegetation following a rare prolonged spring precipitation event,
- prominent topographic depressions.

The DEM for the Piyami Drain watershed was interpolated from point elevation data using the TOPOGRID command within ArcInfo (Hutchinson, 1989). The elevation data were provided by AltaLIS (Calgary, Alberta), the agent for Spatial Data Warehouse, which is a not-for-profit organization maintaining and promoting Alberta's digital mapping. The elevation data were comprised of regularly spaced 100 m elevation points with additional spot points (i.e., road intersections), and elevation points along landscape break-lines (i.e., coulee ravine thalwegs and ridges). Following the work of Quinn et al. (1991) and Kienzle (In Press) the DEM was interpolated to a 10 m grid cell size. The resulting cell values were kept as floating point numbers to avoid the flow direction problems associated with integer grids (Freeman, 1991; Garbrecht and Martz, 1997; Rieger, 1998; Turcotte et al., 2001).

3.1 Field scale results

The variable template model (Level II) was implemented for the field scale application. The extent of the field scale study consisted of an area enclosed by two adjacent township roads and three adjacent range roads (Figure 10a). Thus, the study area dimensions were approximately 3.2 km by 3.2 km (2 by 2 miles), with a total road length of approximately 16 km (10 miles). Approximately 4.8 km of road (3 miles) were assigned to each of the three classification categories (viz. flat cross-sectional profile, raised road, road with adjacent ditches) (Figure 10a). A ditch-to-road height of 1 m was assigned to the raised road template. The roads with adjacent ditches were assigned a ditch-to-field height of 0.5 m and a ditch-to-road height of 1.5 m.

The drainage pattern derived using the conventional DEM-derived approach (viz. D8) did not show any indication of the presence of a runoff collector network adjacent to the road locations (Figure 10b). In contrast, Figure 10c shows the modified drainage pattern created with the variable template model. The runoff collector network is easily distinguishable on both sides of the road when the road is classified as road with ditches (Figure 10c). The presence of a runoff collector network is also clearly visible on the upslope side of the road classified into the raised road template. Because the grid cells adjacent to the road with a flat cross-sectional profile were not identified as being influenced by the adjacent road, the modified drainage pattern was identical to the DEM derived pattern. When the modified drainage pattern was examined in its entirety, the field scale test application effectively showed that roads and ditches significantly modify drainage patterns at the field scale. Therefore, one can infer that biophysical processes modeled within the watershed would also differ because of the effects of roads on overland flow directions.
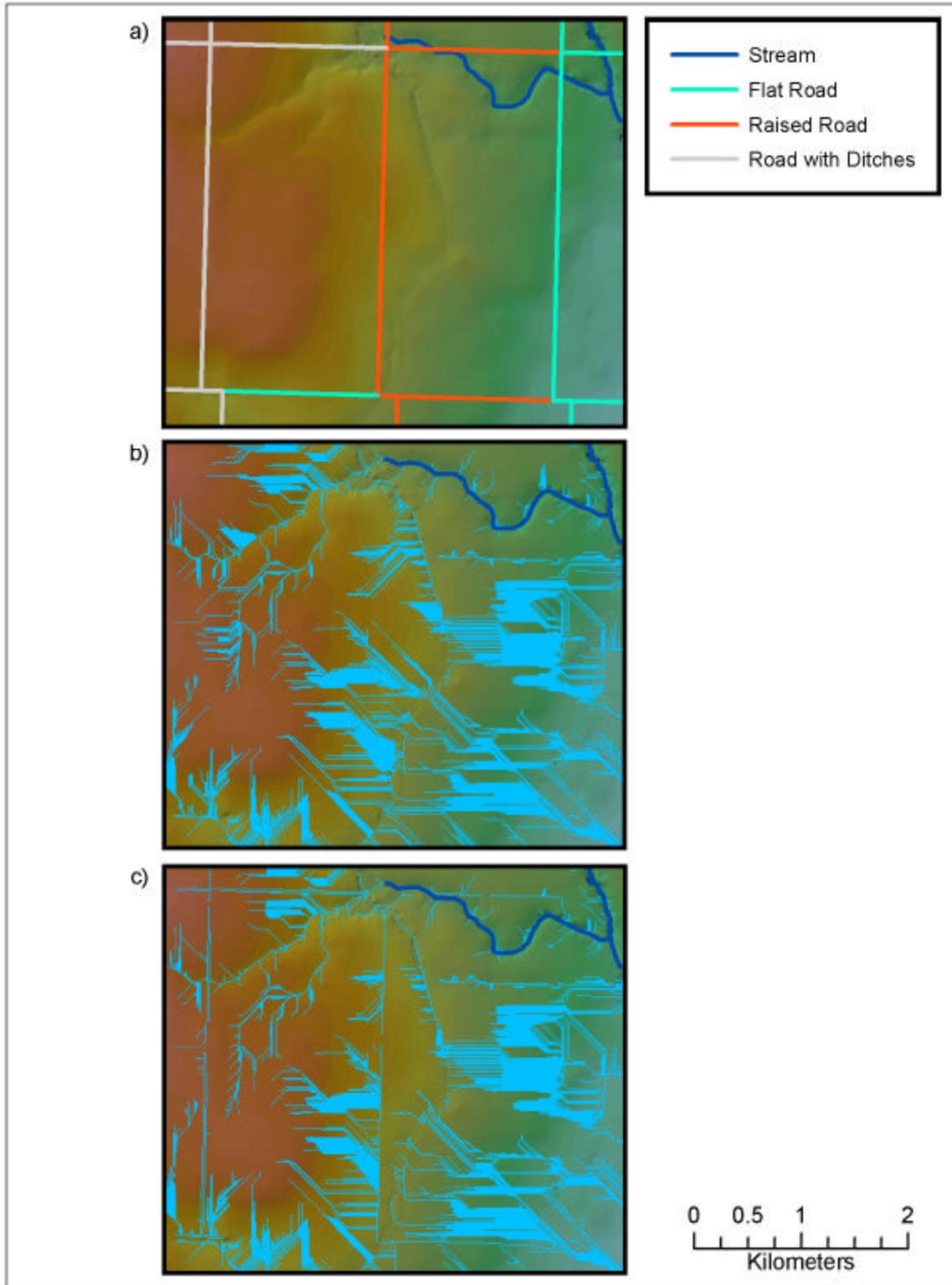
Figure 10. Field scale drainage patterns: (a) Road classification base map, (b) DEM-derived flow accumulation map, (c) REA-derived flow accumulation map

To demonstrate the implications of DEMs failing to represent roads and ditches, the REA was also implemented using the single template model (Level I). A raised road cross-sectional profile was assigned to the previously described road network with a ditch-to-road height of 1 m. Figure 11a shows the location of all grid cells that the DEM-derived flow direction matrix predicted runoff would cross, or breach a road. In contrast, Figure 11b shows the locations of all predicted road breach locations following re-routing with the REA. The total length of road breaches predicted by the topographical DEM-derived flow direction matrix corresponded to 79% of the total road length (1,620 breach grid cells out of 2,043 road grid cells). Following re-routing with the REA the number of road breach locations reduced to 18 (<1% of the total road length). Because significant overland flow could theoretically cross the road at each predicted road breach location, these locations are likely to correspond to either culvert locations or to show some indication of historic runoff ponding (viz. cattail growth, dead vegetation). A field investigation revealed 14 of the 18 predicted breach locations contained culverts (78%). One of the 14 confirmed culvert locations was located approximately 75 m from the predicted breach location within a relatively flat area. Of the 4 locations without culverts, one contained standing water, and a second corresponded to an area of dead vegetation along the edge of a cultivated field that was flooded during a rare spring precipitation event. The ditch-to-road height at one of the remaining three locations was significantly higher than 1 m. Therefore, a larger ditch-to-road height would have been more appropriate and may have eliminated this breach location. The field investigation also revealed that two additional road crossing culverts were located in the study area, but were not predicted by the REA. Although a single road cross-sectional template for the approximately 16 km of road was a gross generalization, the modified flow direction matrix seemed to be more realistic than the flow direction matrix derived from the DEM alone.
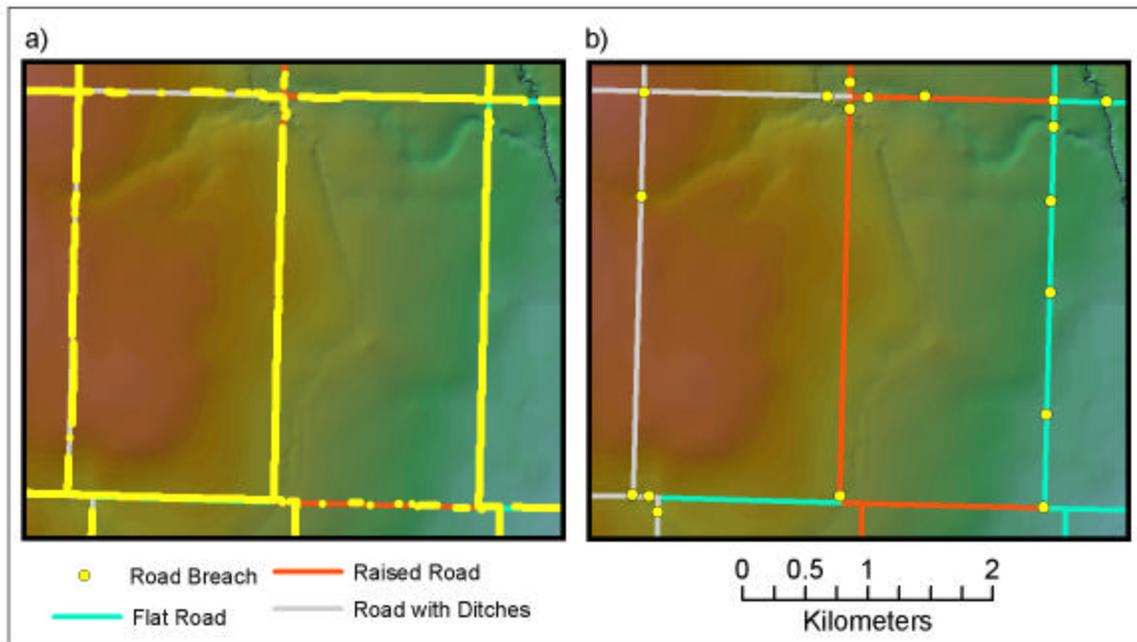
Figure 11. Field scale road breach locations: (a) DEM-derived drainage pattern, (b) REA-derived drainage pattern

3.2 Watershed scale results

The drainage patterns were modified for the entire south fork of Piyami Drain using the variable template model (Level II). Through a field survey each road segment in the watershed was classified into three categories including: flat cross-sectional profiles, raised roads, and roads with adjacent ditches (Figure 12). To gain a better understanding of the typical road cross-sectional profiles within Piyami Drain, 10 road cross-sections were surveyed with a theodolite (Table 1). The surveyed cross-section locations were selected to include the range of road cross-sectional profiles in the watershed. The ditch-to-road and ditch-to-field heights were set from a subjective analysis of the roads within the watershed and taking into consideration the surveyed cross-sections. A ditch-to-road height of 1 m was implemented for the raised road template. For the roads with adjacent ditches template a ditch-to-road height of 1.5 m and a ditch-to-field height of 0.5 m were used.
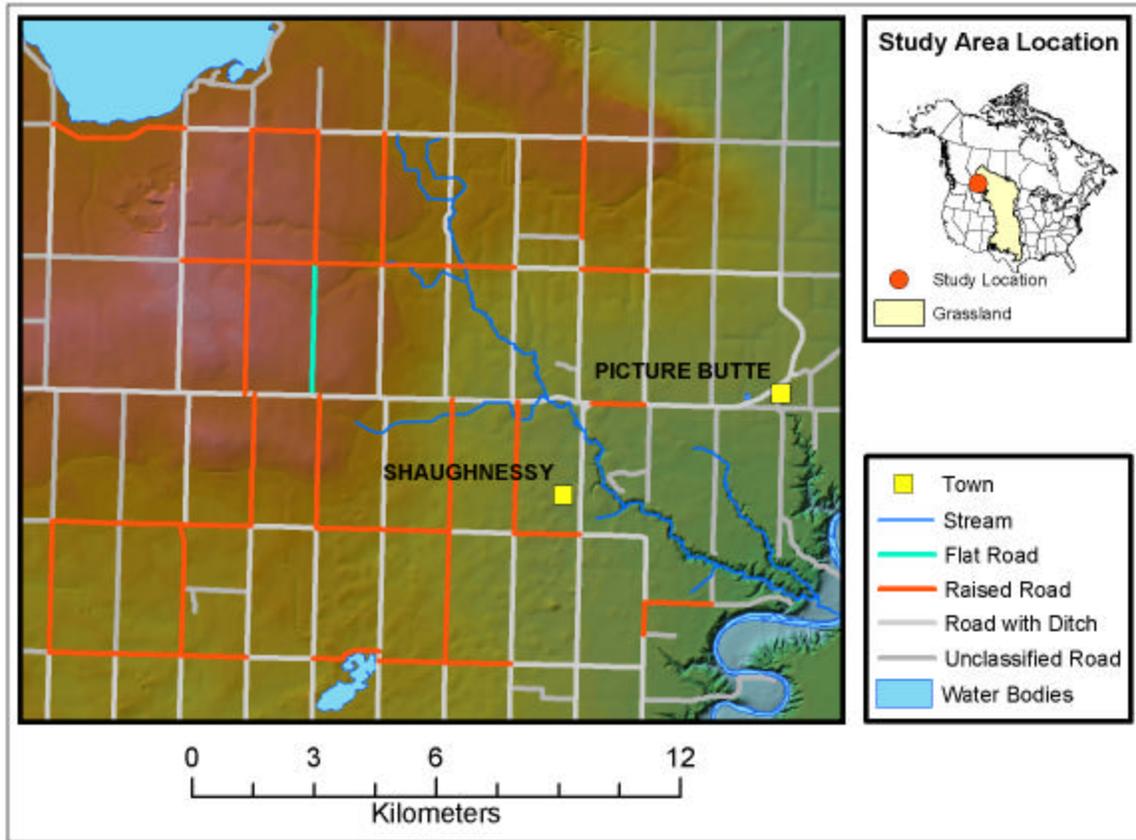
Figure 12. Watershed scale road classification base map used for the variable template model.

Figure 13a shows the watershed delineated using the conventional D8 flow direction algorithm (108 km^2) and the watershed delineated after accounting for roads, ditches, and culverts with the REA (114 km^2). The watershed boundary was modified in 14 separate locations, however, 93% of the area discrepancy was located in two regions. The difference between the two watershed delineations was quantified using a statistic we refer to as the percent agreement according to equation 1.

$$XPA = \frac{WB}{WD8 + WREA + WB} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots \text{[Equation 1]}$$

Where:
XPA = watershed % agreement
WD8 = area delineated by the D8 algorithm only
WREA = area delineated by the REA algorithm only
WB = area delineated by both the D8 and the REA algorithms

Equation 1. Percent agreement statistic.

The percent agreement statistic was meaningful because regular area comparisons did not take into consideration the spatial agreement of two regions, whereas the percent agreement statistic did. The

percent agreement between the Piyami Drain watershed derived with the D8 flow direction matrix and the watershed derived from the flow direction matrix following the implementation of the road enforcement algorithm was 94%.

Table 1. Surveyed ditch-to-field and ditch-to-road heights within Piyami Drain.

Ditch to Field Height (meters)	Ditch to Road Height (meters)
1.600	1.615
0.440	1.810
--*	1.240
0.670	2.050
0.460	0.870
0.175	0.635
--*	0.910
0.020	0.590
--*	1.070
0.675	1.730
--*	0.440
--*	0.680
0.160	0.800
0.120	1.120
0.650	1.290
0.460	1.090
--*	1.490
--*	1.340
0.165	0.555
--*	0.190
--*	1.615
Average = 0.47	*Average = 1.08*
Standard Deviation = 0.40	*Standard Deviation = 0.50*

* The ditch to field height is not reported because there was not a ditch as these locations; the field may have been either at the same or a greater elevation than the location next to the road.

Whereas the DEM-derived flow direction matrix predicted 152.19 km of road breaches, the road enforcement algorithm predicted 4.81 km (number of grid cells crossing road multiplied by the grid cell size of 10 m). Because a 3.2 km road segment was classified as flat, the breach points along this road were not included in the analysis results. Subsequently, the DEM-derived flow direction matrix predicted 149.64 km of road breaches, corresponding to 14, 964 locations (74% of the entire classified road length). In contrast, the REA predicted 2.16 km of road breaches, corresponding to 216 separate locations (1% of the entire classified road length). Because predicted breach locations indicate where overland flow would cross roads, these locations are likely to correspond to road crossing culvert locations. However, the installation of a culvert is conditional upon the landscape actually producing runoff (Alberta Department of Transportation, 1996). Of the 216 predicted road

breach locations, a field survey confirmed 90 (42%) of the predicted culvert locations. 65 of the remaining 128 predicted breach locations were however, either flooded during a very significant spring rainfall, currently contained standing water, or were prominent topographic depressions. Therefore, 155 (72%) of the predicted road breach locations either contained a culvert or showed direct evidence that confirmed the accuracy of the model. Although 50 (23%) locations did not contain a culvert nor showed direct evidence of overland flow convergence during the field investigation, their appropriateness as road breach locations was neither confirmed nor denied because the local landscape hydrological properties may not have necessitated the installation of a culvert. The remaining 11 (5%) predicted breach locations were considered erroneous, which was likely due to elevation inaccuracies within the DEM.

Culverts located within the runoff collector network facilitate the progression of runoff towards the watershed outlet. In contrast, breach locations without culverts correspond to depressions in the runoff collector network and/or road barriers along landscape thalwegs where runoff accumulates and either evaporates or infiltrates into the soil. Thus, the absence of a culvert effectively isolates the areas upstream of road breach locations from the watershed outlet. We argue that studies concerned solely with runoff parameters measured at the outlet (i.e., water quality, stream flow, sediment concentrations) could benefit from eliminating the hydrologically disconnected areas from the watershed. Further investigations could focus on the areas that are linked to the outlet by overland flow. After the hydrologically disconnected areas were excluded from the Piyami Drain watershed the predefined area that could contribute water, sediment, and contaminants decreased from 114 km^2 to 61 km^2 (Figure 13b). Figure 13b also shows that runoff collector networks create artificial dead drainages, creating a fragmented hydrologicially connected watershed. These results support the conclusions of Montgomery (1994), Wemple (1996), Dijck (2000), Cerdan et al. (2001), Tague and Band (2001), Jones et al. (2001), Snaddon et al. (2002), and Souchere et al. (2003) that runoff collector networks not only influence overland flow directions, but can also increase the runoff efficiency in some areas, while reducing or effectively eliminating it in others.
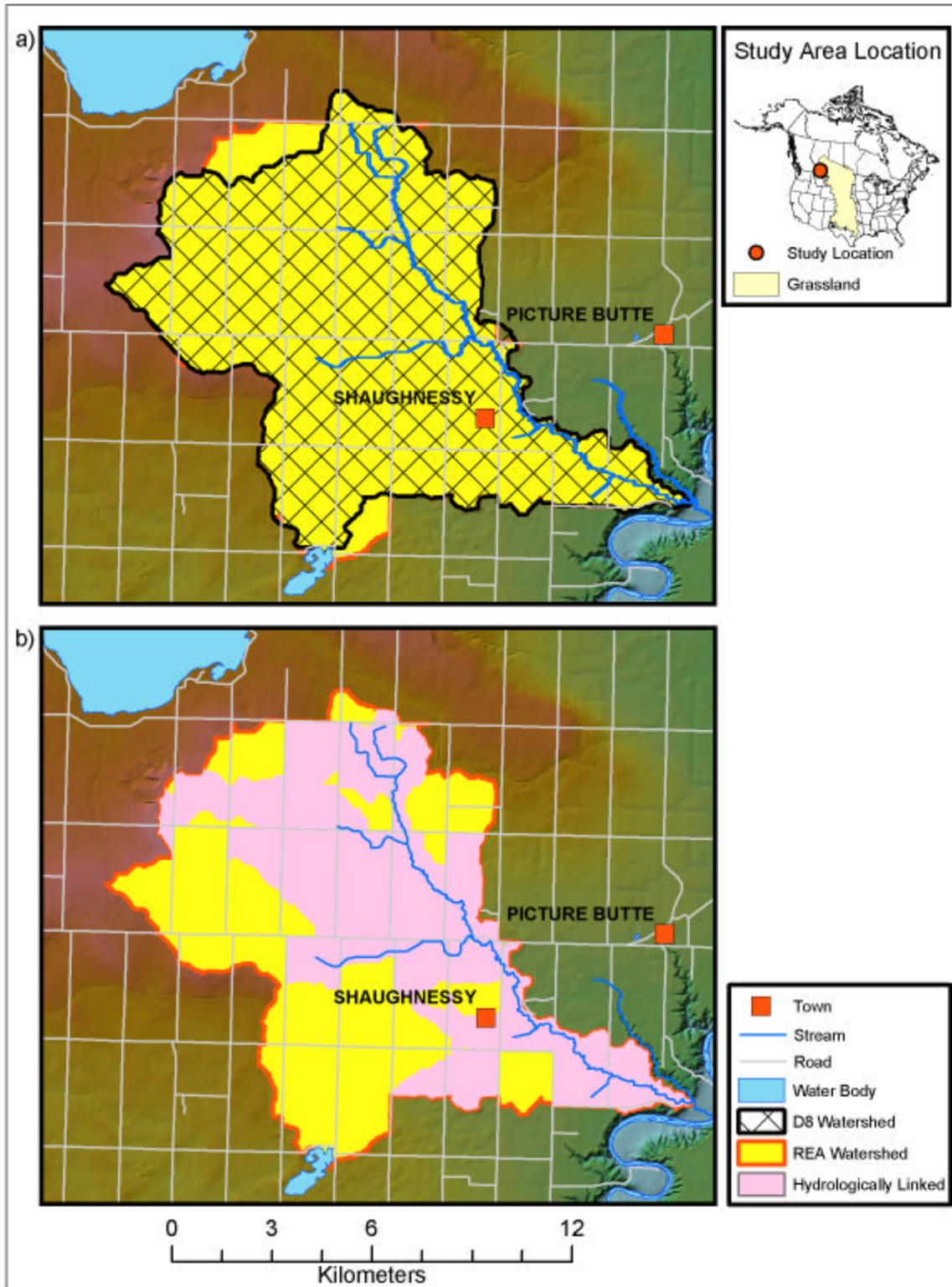
Figure 13. Delineated watersheds: (a) Piyami Drain watersheds delineated with the REA and the D8 algorithm, (b) Piyami Drain hydrologically linked watershed.

4.0 Conclusions

Roads, ditches, and culverts are hydrologically significant landscape features that are not frequently represented in DEMs, necessitating the use of ancillary information to account for their effects when conducting distributed hydrological modelling. The road enforcement algorithm (REA) presented in this paper manipulates flow direction matrices alongside linear landscape features (i.e., roads) by converging the flow patterns towards depressions. Implementing the REA results in the prediction of runoff road crossing locations. Because culverts are installed to facilitate the adequate drainage of roads and field runoff, many of the predicted runoff road crossing locations corresponded to locations where culverts had been installed (42%). However, ditches and elevated roads can also create overland flow barriers. Failing to install culverts effectively disconnects the upslope area from contributing runoff to the watershed outlet. Because the REA can predict culvert locations, a subsequent field investigation revealed that almost half the Piyami Drain watershed delineated with the conventional grid based approach (D8) was hydrologically disconnected from the outlet.

Based upon a subjective analysis of all the roads in the Piyami Drain watershed, we suggest that roads that do not impose overland flow directions according to their orientation are rare in this type of landscape. Thus, the data assimilation process of the REA enables the completion of hydrological studies at scales below the scale that is conventionally governed by the DEM alone.

5.0 Acknowledgements

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