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Spatially-Explicit, Exposure-Based Assessment of Surface Water Vulnerability from Land Use Threats for Time-Efficient and Cost-Effective Watershed Development Planning

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Abstract

The utility of a spatially-explicit, exposure-based model was examined for its suitability as a tool for rapidly assessing surface water vulnerability in watershed planning. This simple GIS-model uses three types of easily obtainable spatial information: (1) sources of land use-induced change; (2) intensity of watershed drainage; and (3) sensitivity of drainage basins to change. This model was applied to the Thomas Brook watershed in Nova Scotia, Canada, which has been the site of previous studies, conducted over multiple years, using detailed, effects-based, hydrologic models. Doing so allowed us the opportunity to compare the two approaches. Results showed a good concordance in the derived mapped outputs between the two models. Given the rapid ease and inexpensive cost of using the GIS, exposure-based model, we believe it to offer great promise in terms of prioritizing locations for further study or for intervention of best management practices, as well as for planning where to best direct future water-sensitive development through build-out analyses.

Keywords

Watershed GIS Analysis, Surface Water Vulnerability

1. Introduction

Deterministic models have been used to simulate complex processes in the movement of water, sediment and contaminants in the scientific study of watersheds [1]. Implicit in this work, frequently undertaken by environmental engineers, is that such information will be useful to the sustainable management of these landscapes in terms of protecting receiving waters (as well as their dependent wildlife and humans) from deleterious land-use practices. Limitations in the widespread adoption of this approach, especially among environmental planners, concern issues related to the availability of the specialized, sometimes site-specific, data and the degree of expertise both needed to run the models. The labor-intensive nature of developing these models in terms of educating operators is such that the models are often generated as part of multi-year graduate theses.

The accelerating pace of the environmental degradation of watersheds necessitates developing more rapid approaches for identifying those locations most in need of applying best management practices (BMPs) to protect ecosystem services [2] [3]. In consequence, for the wide-scale assessment of numerous watersheds in a region, there has been a shift away from effects-based variables that measure or model localized impacts of anthropogenic disturbance, to exposure-based variables that are based on spatially-mapped appraisals of potential stressors [4] [5] [6].

Of paramount importance for water-sensitive land use planning is the need to be able to rapidly prioritize the suitability of different locations in order to regulate land use development in the most environmentally benign way possible [3] [7]. As Arendt [8] stated: "Every new development should be based upon a fairly thorough (but not necessarily costly) analysis of the site's special features, both those offering opportunities and those involving constraints." The spatially-explicit identification and relative screening of potential future development sites through geographic information system (GIS) analysis has proven to be a useful tool in time-efficient and cost-sensitive water sensitive planning, as for example in protecting lakes from soil erosion [9], preserving the recharge of aquifers [10], and creating alternative futures scenarios [11].

One useful (and simple to use) GIS-based model for predicting the aquatic impacts of site development is that of Purdum [12]. Here, the vulnerability of surface waters can be rapidly assessed based on three types of generally easily obtainable spatial information: 1) sources of land use-induced change; 2) intensity of watershed drainage; and 3) sensitivity of drainage basins to change. The most useful outcome from the model is that it provides a quick and inexpensive logical framework from which to rank sites in relation to their likelihood of impacting streams [3]. Either some particular locations should be avoided altogether in terms of future development, or they can become the target of further, more detailed study. The GIS-model will also be useful in targeting future research activities to the particular areas deemed most important in a watershed. For as Purdum [12] stated: "Site-specific investigation of signs of eutrophication, erosion, pollution, wetland loss and stream channelization are made more efficient by reducing the problem to a relatively small number of locations where they are most likely to be found."

Purdum [12] pioneered his spatial, exposure-based model for a 9.5 km-square township in Michigan of predominantly agricultural land-use, which contained portions of 7 watersheds. The model results are derived maps of water vulnerability and are of course particular to each specific study area. Of more interest is whether the model methodology can be applied to other situations and thus has potential to be adopted as a tool for environmental planning. The purpose of the present study was therefore to examine the utility of the Purdum model by applying it to a single watershed in Nova Scotia, Canada that has been the object of previous investigation through use of detailed, process-based, hydrological models [13] [14] [15] [16].

2. Material and Methods

2.1. Description of Study Area and Data Sources

Purdum's water vulnerability assessment model [12] was applied to the Thomas Brook watershed, located in the Annapolis Valley of Nova Scotia (**Figure 1**).

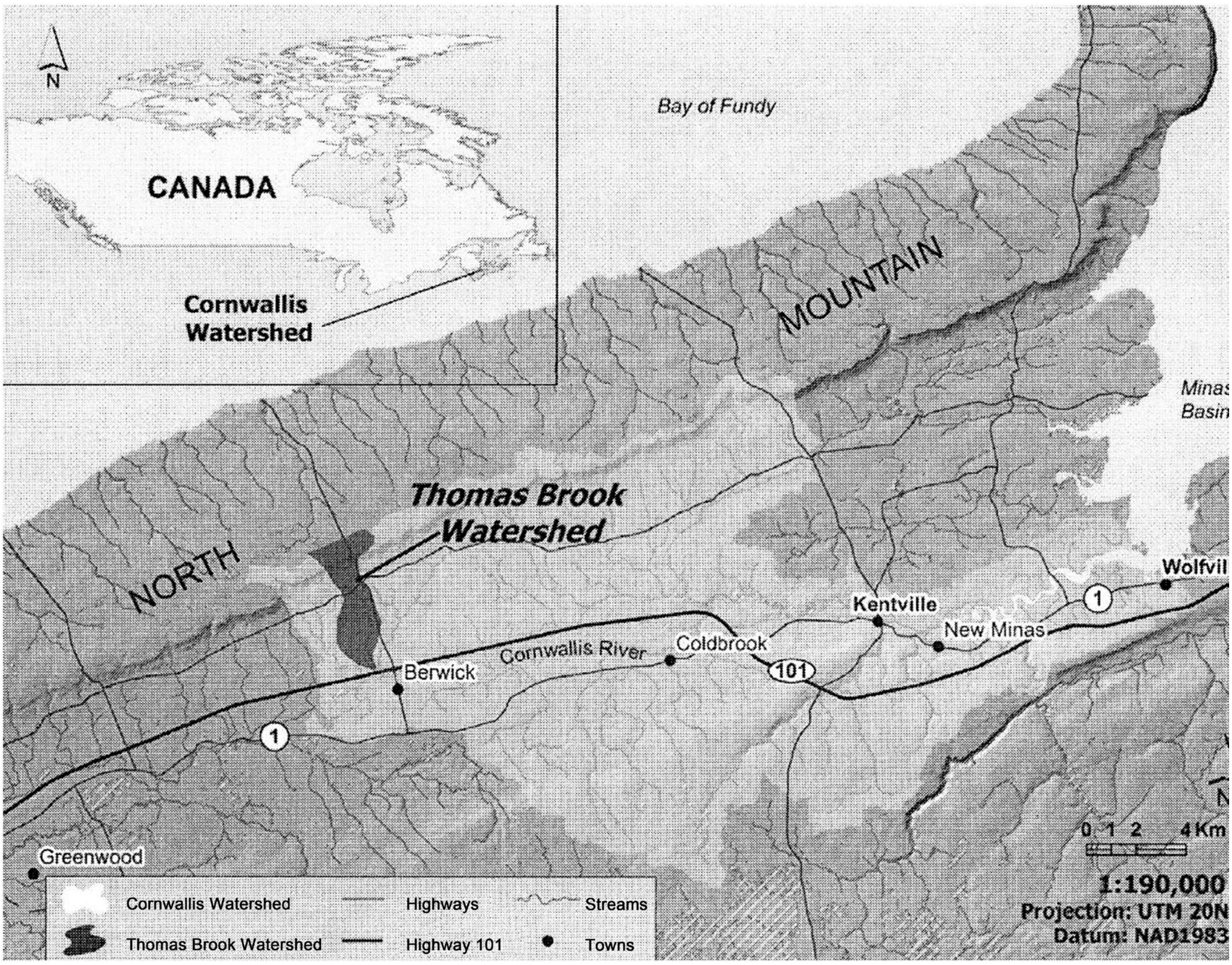


Figure 1. Location of Thomas Brood watershed within the Cornwallis River Catchment in Nova Scotia, Canada (65.4˚ - 64.0˚ latitude; 45.3˚ - 44.6˚ longitude). Source: [15].

This small, 784 ha watershed is part of the larger 360 km^2 Cornwallis River Catchment draining into the Bay of Fundy. The stream network is relatively simple with several upland streams merging into a single channel about a third of the way down the watershed (**Figure 2**), with a total linear drainage length of about 6 km, all being fed by rainfall, ephemeral rivulets, and groundwater seepage. The average channel slope is 3.5%, being steeper in the upper watershed (>10%) and shallower in the lower reaches (0.5% - 1.3%) [13]. Soils are predominantly reddish brown sandy loam [17] (**Figure 3**). Land-use is varied [15], being primarily (ca 57%) agriculture [14] (**Figure 4**) with large patches of forest in the upper watershed (**Figure 5**) and numerous dwellings in the mid- to lower watershed (**Figure 6**).

The Thomas Brook watershed has experienced degradation of both surface and groundwater quality due to agricultural and residential development [13] [14]. Because of this, the watershed was selected to be part of a long-term research program of Agriculture and Agri-Food Canada [18]. The Watershed Evaluation of Beneficial Management Practices (WEBs) program was set up to assess the environmental and economic impacts of different BMPs through hydrologic modes of sediment and nutrient export [15] [16]. As well, due to being labelled as one of the most attractive places in all of Canada in which to live, the predominantly agrarian Annapolis Valley is under threat from development, as witness to newspaper articles bearing titles such as “Farmers losing fight against urban sprawl”, “No farms means no food”, or “Giving away the farm”, for example.

The model is based on an existing database comprised of 12 parameters available from easily obtainable government and academic sources: from the Government of Nova Scotia’s GeoNOVA portal: topography (orientation, derived from DEM), topography (slope, derived from DEM), water table (seasonal high), water (wetland type), open water (predominant type, *i.e.* lake, river, stream, etc.), woodlands (presence, absence, type), vegetation (predominant type, *i.e.* forest, grass, etc.), transportation (type, *i.e.* gravel, bridge, class of highway), urban land (dwellings, from zoning of land), and agriculture (existing agricultural land uses); from Natural Resources Canada: soil erodibility index (derived from detailed soil survey); and from Dalhousie University’s GISciences Centre: water (watershed boundary for Thomas Brook catchment area).

2.2. Description of Model

Detailed explanations behind the rationale for including model variables, as well as the step-by-step developmental process, are described in [12], from which the following shortened description is derived. Surface water vulnerability was assessed based on the serial integration and evaluation of three types of spatially-explicit geographic data: 1) *Sources of Land Use-induced Change*; 2) *Intensity of Drainage*; and 3) *Sensitivity of Drainage Basins to Change*. The model is based on the step-wise inclusion of information contained within three to four simple

Figure 2. Main channel of Thomas Brook in the lower portions of the eponymous watershed.

Figure 3. Easily erodible sandy loam soil in the Thomas Brook watershed in the Annapolis Valley of Nova Scotia.

Figure 4. Agriculture (corns, strawberries, and grains) is the primary land use in the Thomas Brook watershed.

Figure 5. The upper part of the Thomas Brook watershed is covered with large patches of forests.

Figure 6. Numerous dwellings occur in the lower half of Thomas Brook watershed.

rankings categorized based on values obtained from the literature and expressed (*i.e.* mapped) as dimensionless variables (**Figure 7**).

2.2.1 Step 1: Derivation of the Sum of Sources of Land Use-Induced Change

The first step of model development is to determine the *Sum of Sources of Land Use-induced Change*. This was determined by integrating database overlays from 5 spatially-assessed variables: nutrient loading, erosion and sedimentation, stormwater runoff, adjacent wetland loss, and alteration of stream morphology (**Figure 7**).

The potential for nutrient (both phosphorus and nitrogen) loading from each location is dependent on land use and vegetative cover. Nutrient loading weights were assigned in relation to agriculture (highest), urban (medium), and forests (lowest) [12].

The potential for erosion and sedimentation is based on the spatial assessment of three determinants: soil typology combined with slope; distance from surface water; and land use. The relative erosion hazard is estimated by the nature of the soils and the slope of the land. Each location was given a value in relation to high, moderate, or low soil erodibility in relation to categorization by the USDA Soil Conservation Service [19], and topography grouped as low (0-6%), moderate (7-14%), and high (15+%) slope classes. The distance from water reflects the well-known protective role of buffers in reducing soil transport [20]. Locations more than 200 m away are designated as low, 100-200 m as moderate, and less than 100 m as high potential threats. The combination of these two determinants in a matrix were then multiplied by a weighting factor based on the (rational method-determined—[21]) coefficients of runoff in relation to the degree of imperviousness [22].

The stormwater runoff hazard assessments (*i.e.* coefficients of runoff) were ranked as very low, low, moderate, severe, and very severe based on the land uses of urban, cultivated, residential, forest, road/bridge as in [23], and of stream proximity as in [12].

Because wetlands operate as hydrological sponges and purifying kidneys on the landscape [24], estimates of their historic loss are important in assessing land use-induced change. Wetland loss adjacent to surface waters is of more consequence. Each location's historic wetland loss was assessed as low, medium, high, or severe in relation to its current land use, using, as did Purdum [12], the same weighting for the stormwater runoff hazard assessment obtained from Marsh [23].

Because streams in urbanizing environments are in states of dynamic disequilibrium [25], they can negatively impact aquatic quality in periods of flooding and low base-flow. Historic alteration in steam morphology, ranked as low, medium, or high, was assessed in relation to current land use, using, as did Purdum [12], the same weights as before from Marsh [23].

Each of these 5 individual sources of land use-induced change generate their own mapped output (**Figure 7**). These are then simply summed together to create an integrated value reflecting the sum of these changes which is categorized as high, medium, low, or none on the resulting map of the *Sum of Sources of Land Use-induced Change*.

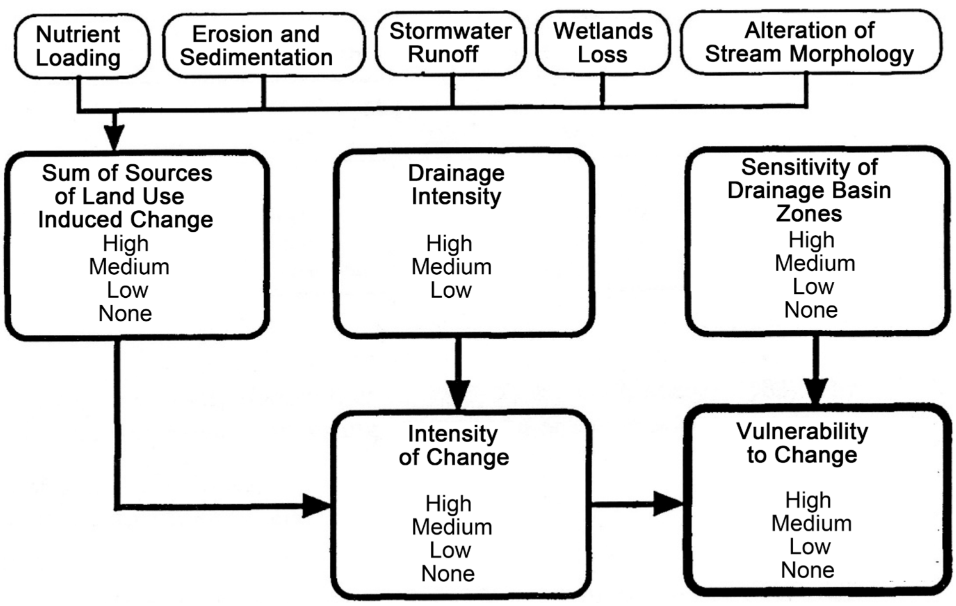
2.2.2. Step 2: Derivation of the Intensity of Change

Identification of the locations more susceptible to change is estimated by the drainage intensity, which is dependent on the area of the drainage basin, land use and cover typology, and the movement of rainfall through the drainage network [23]. By using a simulation of a 100-year storm, the estimated peak discharges are compared and categorized as low, medium, or high potential energy in the landscape to affect change. Output was calculated using the "flow accumulation" tool in ArcGIS with the DEM as an input. This allows an output of accumulated weight of all cells flowing into adjacent downslope cells which are then reclassified into the ranks above.

The assessment of the *Intensity of Change* is determined from a matrix combining each location's drainage intensity with its previously derived *Sum of the Sources of Land Use-Induced Change.* These values are rated and shown on the resulting map as very low, low, moderate, high, very high, and severe potential energy (**Figure 7**). The present model uses 7 categories rather than Purdum's 4 due to more refined splitting of the total range observed.

2.2.3. Step 3: Derivation of the Vulnerability to Change

The shape of the land will influence the movement of runoff and the consequent transport of contaminants [26] [3]. The potential for this to occur is based on a location's surrounding topography [12]. The output from the present model is the result of a matrix of ranked proximity to a stream, depth of the water table, and flow accumulation. Sensitivity of drainage basin zones were categorized as low for upland locations where dispersed overland sheet flow will occur, medium



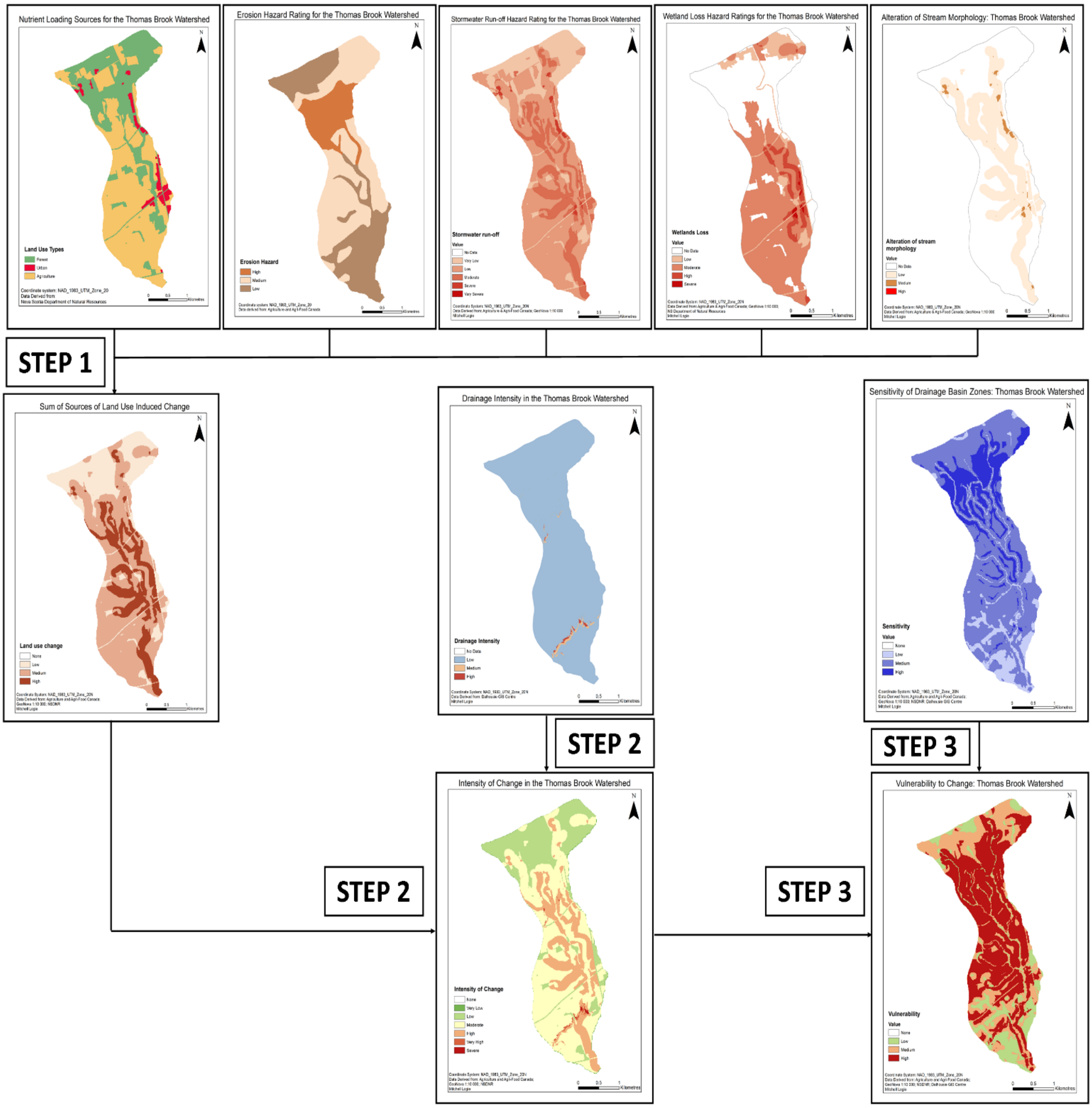


Figure 7. The exposure-based GIS model from Purdum [12] (textural representation shown in upper panel) used in the present study for Thomas Brook (schematic, mirroring thumbnail representation shown in lower panel) which follows the identical positional order. Component variables (from left to right in top row of either panel) of nutrient loading sources, erosion and sedimentation hazard, stormwater runoff hazard, wetland loss hazard, and alteration in stream morphology, are integrated (*i.e.* labelled as "STEP 1" in lower panel) to generate the *Sum of Sources of Land Use-induced Change* (left side box in middle row of either panel). The latter is then combined (*i.e.* labelled as "STEP 2" in lower panel) with *Drainage Intensity* (central box in middle row of either panel) to generate the *Intensity of Change* (left/central box in bottom row of either panel). Finally, this is then combined (*i.e.* labelled as "STEP 3" in lower panel) with the *Sensitivity of Drainage Basin Zones* (right side box in middle row of either panel) to produce the final *Vulnerability to Change* map (right side box in bottom row of either panel).

for collection zones in which runoff is concentrated, and high for conveyance zones where runoff can directly enter surface waters.

The final assessments of the *Vulnerability to Change* of surface waters is determined from a matrix combining each location's sensitivity of drainage basin zones with its previously derived *Intensity of Change* (**Figure 7**). These values are rated and shown on the resulting map as low, moderate, and high.

3. Results and Discussion

3.1. Spatial Description of Watershed Assessments

Each of the 5 sources of land-induced change produces its own output map (**Figure 7**). The three land use categories used in our present application of the Purdum model accurately condense the earlier, more detailed designations of 18 land use typologies used by Ahmad *et al.* [15] to run their engineering SWAT (Soil and Water Assessment Tool) model which simulated agricultural nonpoint source pollution in the Thomas Brook watershed. Most of the upper or top reaches of the watershed are covered with forests, with urbanization being largely centered along the central-eastern edge, and with much of the middle and lower or bottom of the watershed being agricultural. Ahmad *et al.* [15] show maps of soil typology and slopes for the Thomas Brook watershed. The rapid derivation of erosion hazard ratings for the present model adequately captures this spatial information determined from the labor-intensive engineering model. Locations of high erosion hazards were found to occur in regions of rock outcrop and steep riparian terrain, mostly in the central "neck" area of the watershed. Locations of low erosion hazard occurred in about half of the top reaches and most of the bottom reaches of the watershed, the rest of the watershed being categorized as medium erosion hazard. Derivation of stormwater runoff hazard ratings closely parallels land use. Very severe and severe categories were restricted to developed locations, and the very lowest and low categories occurred respectively in forested and in agricultural locations. Of more interest is that most of the riparian zones received a category of moderate runoff hazard. Most of the Thomas Brook watershed (from the central "neck" downstream) was designated as having a wetland loss hazard rating of moderate. Locations of high and severe rating were restricted to the riparian corridor in the bottom half of the watershed. In terms of the alteration of stream morphology, the riparian zones were predominantly categorized as low hazard. Only a few isolated locations, those with residential development or roads, were designated as medium hazard. No designations of high stream alteration hazard were found.

Together, all this information was integrated to produce the map of the *Sum of Sources of Land Use-induced change* shown in **Figure 8**. Most of the Thomas Brook watershed is categorized as having medium land use change. Locations of high land use change are predominantly restricted to the riparian zones within the central and bottom regions of the watershed, and locations of low land use change occur within the top reaches of the watershed.

With the exception of a few locations in the central "neck" region and a linear

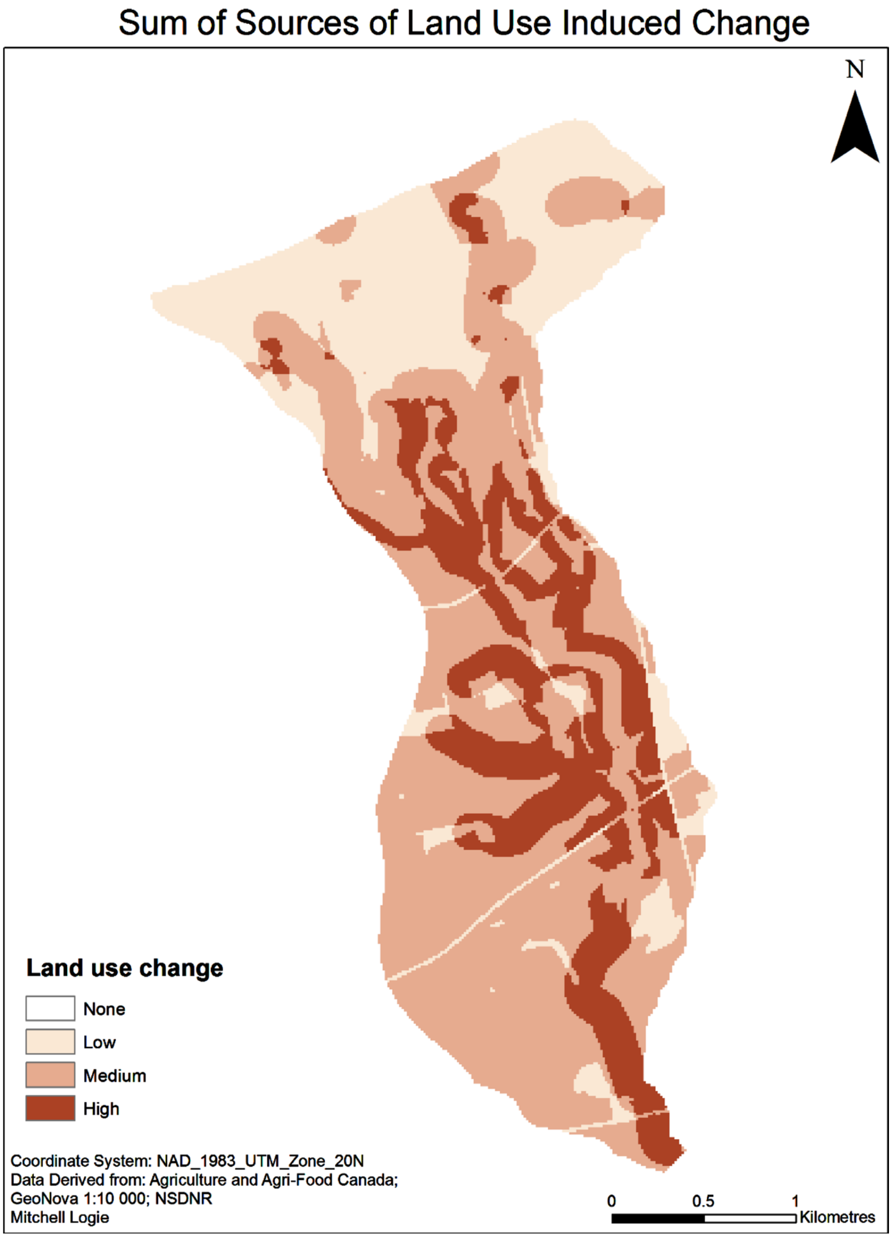


Figure 8. *Sum of the Sources of Land Use-induced Change* map for Thomas Brook watershed. Classification categories are dependent on integration of 5 sources of land-induced change rankings (*i.e.* nutrient loading, erosion and sedimentation, stormwater runoff, wetlands loss, and alteration of stream morphology), as shown in Figure 7 and explained in text.

strip through the bottom region of the watershed, both of which were categorized as having medium or high drainage intensity ratings, the rest of the Thomas Brook watershed was designated as low drainage intensity. Combining this information with the *Sum of Sources of Land Use-induced change* produces the map of the *Intensity of Change* shown in Figure 9. Much of the top watershed was categorized with a low rating, whereas locations distant from the stream in the central and bottom of the watershed were categorized as moderate. Much of the linear length of the riparian zones were categorized as having a high intensity of change, and only a few locations in a contiguous band through the bottom of the watershed were designated with very high or severe ratings of intensity of change.

Sensitivity of drainage basin zones depends on topography. For the Thomas Brook watershed, locations of highest sensitivity occurred in the region of greatest elevation change, as shown in the DEM-determined slope map in Ahmad *et al.* [15]. These included the ridge crest which spans the width of the watershed just above the "neck" region, as well as riparian zones in the central region

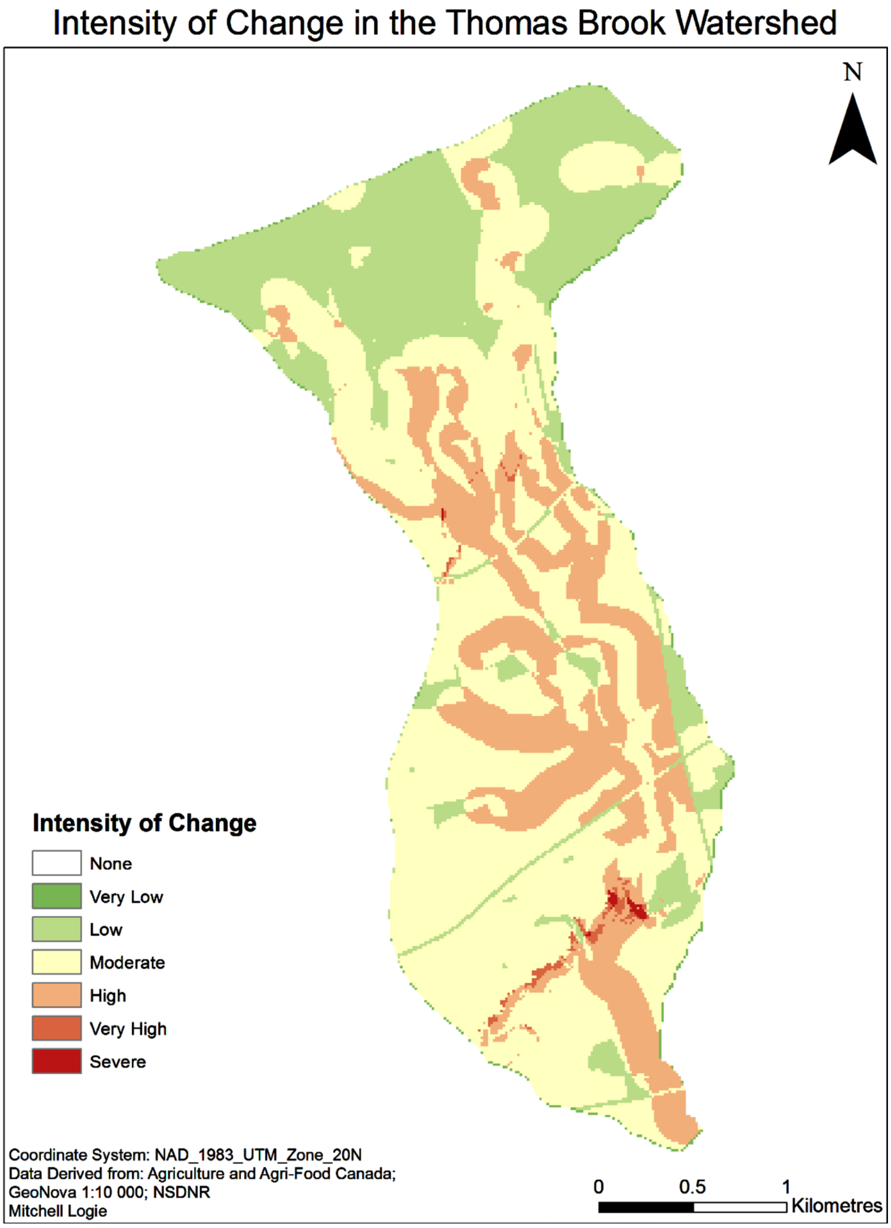


Figure 9. *Intensity of Change* map for Thomas Brook watershed. Classification categories derived from rankings in **Figure 8** combined with those for drainage intensity, as shown in **Figure 7** and explained in text.

(Figure 10). Locations of the lowest sensitivity occurred in the bottom reaches of the watershed, where slopes were the lowest. The bulk of the watershed was categorized as medium drainage basin sensitivity.

The integration of this information with the *Intensity of Change* data produces the final map of the *Vulnerability to Change* shown in Figure 11. Locations in the topmost reaches of the Thomas Brook watershed are categorized as being of predominantly medium threat from land use-induced change to surface water vulnerability. Locations in the bottom of the watershed are categorized as being of largely low threat from land use-induced change to surface water vulnerability. And locations in much of the central region of the watershed are categorized as being of high threat from land use-induced change to surface water vulnerability.

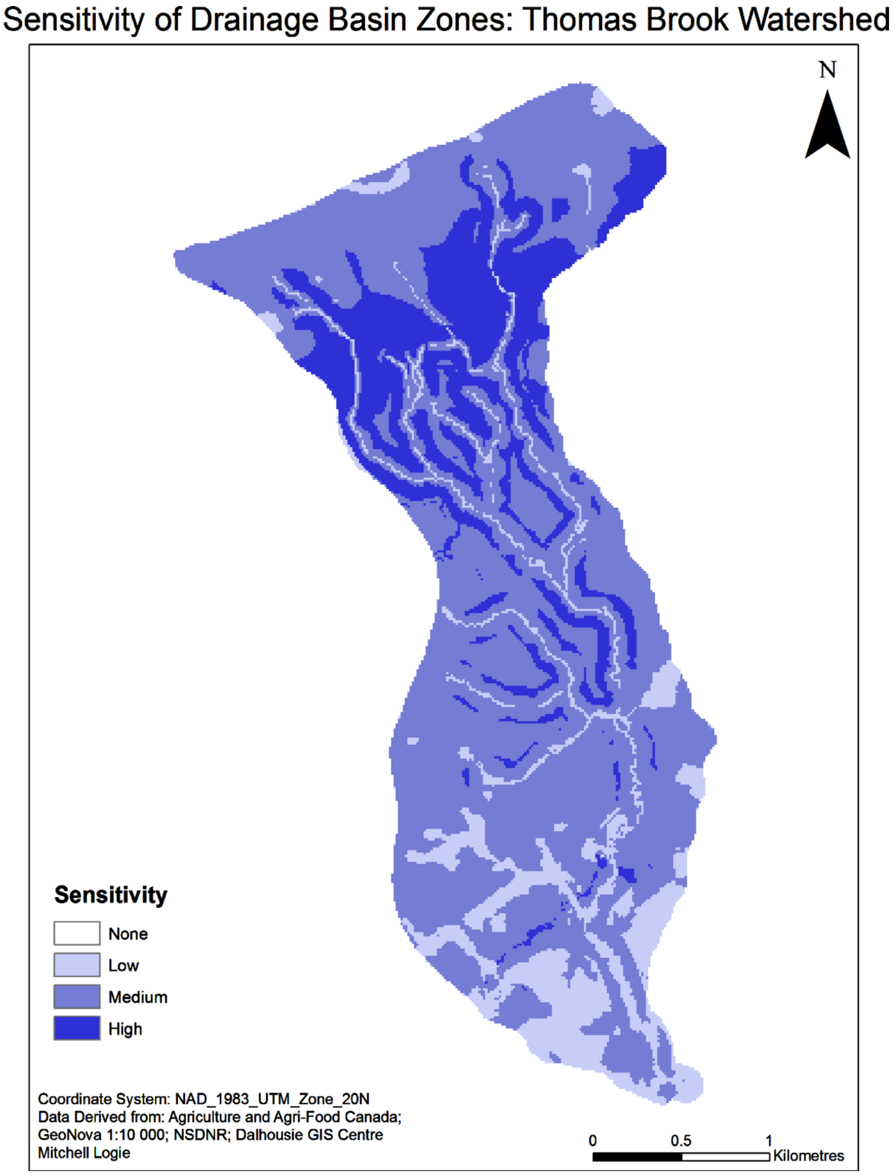


Figure 10. Sensitivity of drainage basin zones map for Thomas Brook watershed. Classification categories determined from rankings of drainage flow, as explained in text.

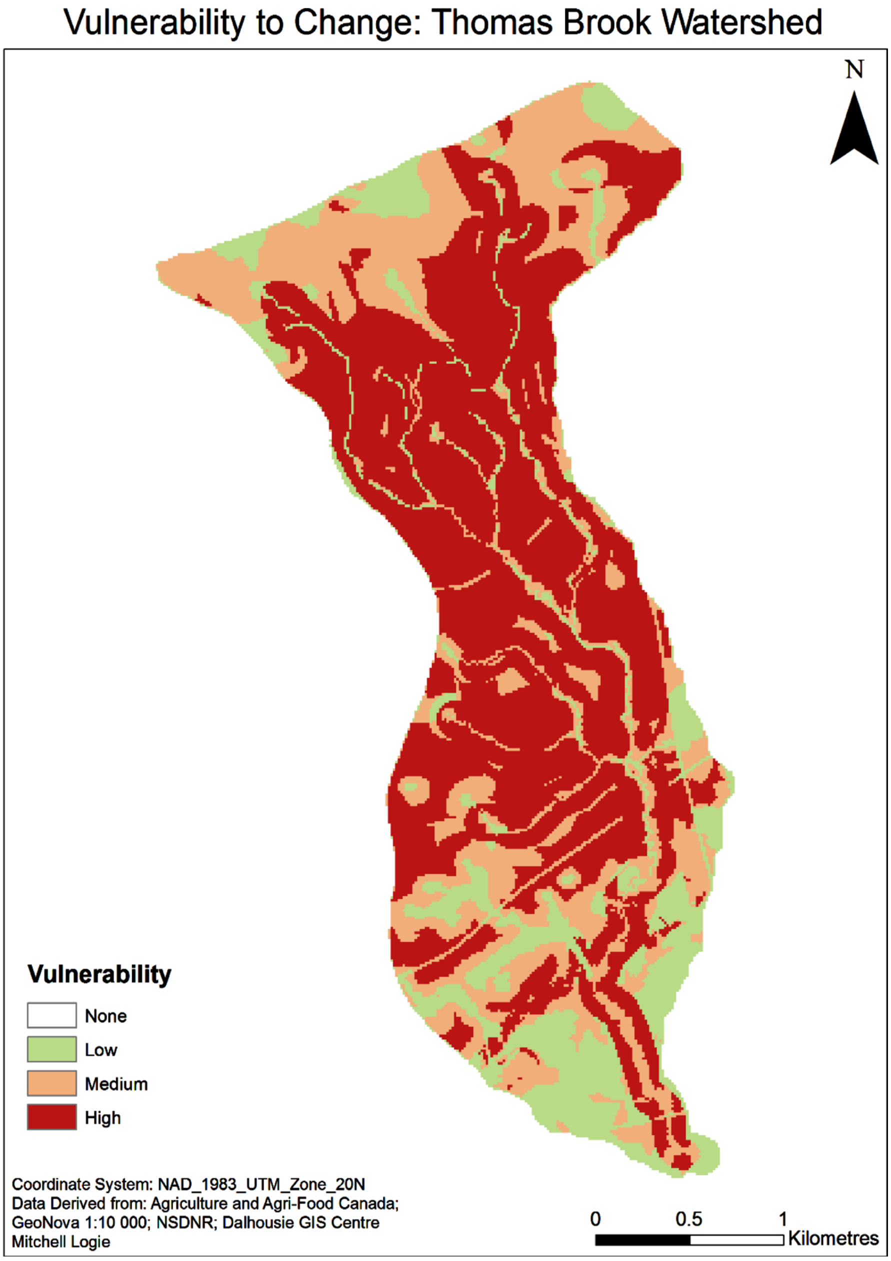


Figure 11. Final *Vulnerability to Change* map for Thomas Brook watershed, useful for prioritizing locations for further study or future management interventions, as well as for planning future water-sensitive development. Classification categories derived from rankings of drainage sensitivity in Figure 10 combined with those for intensity of change in Figure 9, as shown in Figure 7 and explained in text.

3.2. Implications for Water-Sensitive Land-Use Planning

From the present GIS analysis, using Purdum's [12] spatial, exposure-based model, a suggestion can be made that in terms of water-sensitive planning, it would be wisest to direct future development in the Thomas Brook watershed to the bottom reaches where the predicted threats to stream vulnerability from land use-induced change will be the lowest. If this is not possible, the next most favorable region for development would be the top reaches where the predicted threats to stream vulnerability from land use-induced change will be of medium likelihood. Only as a last resort should the central rejoin of the watershed, where the predicted threats to stream vulnerability from land use-induced change will be the highest, be targeted for future development.

It is important to remember that water-sensitive planning assessments of surface water quality vulnerability (in addition to its contributing factors of wetland loss and presence and extent of forested buffers), such as measured and used in the present GIS model, are but one part of a framework of comprehensive watershed development planning in both professional and pedagogical undertakings. Other variables to consider include wildlife-sensitive planning (endangered species, biodiversity, fragmentation, connectivity), site amenities (agricultural potential, visual quality, historic/cultural resources), and site construction and maintenance (energy and microclimate, projected construction costs, wastewater treatment) [3].

The GIS model also suggests interesting ramifications for land use planning on a finer spatial scale. For as Purdum [12] stated, "though these sources [of land use-induced change] are mentioned frequently in the literature as contributors to stream and river degradation, their comparative importance is not clear." The final map of the *Sum of Sources of Land Use-induced change* was found to most closely resemble the component map for stormwater runoff hazard, followed by those for wetland loss and for alteration of stream morphology hazards, and least so for those of nutrient loading sources and erosion hazard. For the Thomas Brook watershed, therefore, it appears that the legacy of past and the potential of future hazards for specific sites located within riparian zones will be a greater contributing factor to cumulative land use change than for other sites located upslope and distant from surface waters. In this regard, it is worth noting that the implications of such spatially-explicit results from the exposure-based assessments produced by landscape architects and land-use planners are different from those generated by effects-based, process models used by environmental engineers. This is not surprising given that motivations and methodologies can be dissimilar if not at outright cross-purposes between environmental researchers (environmental engineers) and natural resource managers (landscape architects and watershed land-use planners) [27].

The primary objective of the modeling component of the Canadian WEBs program is to simulate the performance of agricultural BMPs on a watershed scale [18]. The SWAT model used by Ahmad *et al.* [15] requires GIS-based spatial information and temporal climate input variables to simulate levels and movements of water, sediment, and nutrients in relation to varying soils, land uses, and land management schemes. In the case of the Thomas Brook watershed, some of the data necessary for the SWAT model were obtained from a continuous monitoring program spanning years [13]. Ahmad *et al.* [15] calibrated and validated their model, finding it to perform satisfactorily in terms of simulating the export of sediment and nitrate. This led them to conclude that the SWAT model has the potential to be used as a decision support tool for watershed management, though no specific explanation is offered as to how this might be brought about. However, a follow-up paper [16] did use the same approach to simulate how different scenarios of tillage, crop rotation, and fertilizer application would affect crop yield, nitrate leaching, and sediment yield in the Thomas Brook watershed.

The spatial scale of the SWAT model used in the Thomas Brook watershed was based on lumping data from similar hydrologic response units (characterized by their land use, soil type, and slope) in each of 28 delineated sub-basins. Although this is not as spatially-explicit in terms of site-specificity as the present GIS model, it is still useful for enabling comparisons in water protection assessments made between the patterns of the two mapped outputs.

Ahmad *et al.* [15] depict a map showing the spatial distribution of average annual sediment yield measured from the sub-basins to Thomas Brook. The 6 sub-basins found to produce high sediment loads have steeper slopes or have more tillage practices and are situated in the central "neck" region and the top reaches of the watershed. It is important to note that there was a general concordance between these engineering-model results and the high erosion hazard rating category determined for these locations in the present study through use of the rapid GIS-landscape model. Seven of the 13 sub-basins found to produce low sediment loads have shallow slopes and are situated together in the bottom region of the watershed. Again, this matches the low erosion hazard rating category determined for these locations in the present study.

Ahmad *et al.* [15] also depict a map showing the spatial distribution of average annual nitrate export measured from the sub-basins to Thomas Brook. High nutrient losses occurred in 5 sub-basins, three of which were situated in the "neck" region, one in the upper reaches, and the other in the lower reaches of the watershed. There is less concordance between these engineering-model results and the nutrient loading sources mapped in the present study. This discrepancy may exist because the SWAT model determinations can reflect individual point-sources of pollution (farmsteads) that were situated directly above the monitoring inlets of their downstream sub-basins [15].

A benefit of the present spatially-explicit, exposure-based GIS-model is that it identifies those locations with the greatest potential threat to surface water vulnerability. In so doing, these specific locations can become the focus of later, more-detailed research regarding the conceptual modeling of installing any of a number of BMPs of known utility, such as forested buffer strips [28], treatment wetlands [29], storage basins [30], or alternative agricultural practices [31]. Again, our deliberate selection of Thomas Brook as the watershed in which to apply Purdum's rapid assessment, exposure-based model enables comparisons to be made to findings derived previously from a multi-year study generating the detailed scientific, effects-based SWAT model. Ahmad *et al.*'s [15] SWAT model found that the drainage sub-basins of greatest contaminant (sediment and nutrient) loading were located across the "neck" region and within the central area of the top reaches of the watershed, and the sub-basins of lowest contaminant loading were found in most of the bottom reaches of the watershed. Although, using a finer spatial resolution based on precise sites rather than grouped sub-basins, the present GIS-Purdum model identified the very same locations as being meritorious for further study or BMP implementation due to their designation of being a high potential threat to water vulnerability. In other words, there is a close concordance between the two approaches in their identification of those locations in the watershed that are most in need of future research or immediate management.

Steinitz [32] argued that to be effective and efficient, land use planning should progress through a framework of inquisition and investigation by applying the appropriate models of representation, process, evaluation, change, impact, and decision. Process models such as SWAT, popular among environmental engineers, address the question about how landscapes operate, whereas evaluation (assessment) models such as Purdum's, address the question of whether the current landscape is working well. The latter builds upon the former and segues into models for predicting the impacts of land-use changes, which in turn can be used for decision making in terms of avoiding or mitigating those changes [33].

The present study found there to be a close concordance between the results of the process (SWAT) and evaluation (GIS) models. Ahmad *et al.* [15] may be overenthusiastic, and possibly unrealistic, in believing that a labor-intensive, and therefore costly model such as SWAT "has potential to be used as a decision support tool for agricultural watershed management". This is because the scale upon which watershed degradation is occurring necessitates, above all else, rapidity in reaching management decisions [34]. The luxury of having four years for a doctoral student to reach a decision as to which portions of the watershed need "immediate" attention in order to ameliorate soil erosion and consequent degradation of receiving waters is simply not part of real-world praxis [3]. Effective and efficient land-use planning is based on "the notion that complex systems must be met by powerful simplifications that extract the essence of things" [35]. In this regard, we believe that the simple, spatially-explicit, exposure-based model developed by Purdum [12] and investigated in the present study, has the potential, like other GIS-based water-sensitive models [10] [33] [36], to be useful in time-efficient and cost-effective land use planning. Using the present model offers promise as one stage in adopting a logical and operational framework of inquisition and investigation to help achieve the overall goal in watershed management of "being able to assess the vulnerability (the risk of potential harm from the impacts of land-use change) of the area under investigation" [3].

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