A GIS Model for the Identification of a Variable Width Buffer Zone in the Lower Fraser River Watersheds Based on Land Use-Water Quality Interactions

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ABSTRACT

A GIS model for the identification of a Variable Width Buffer to protect surface water quality was successfully constructed. The model was based on the relationships between land use and water quality in the Lower Fraser River watersheds as determined through GIS and statistical analysis of intrinsic, physical and ecological factors contained in land use, soils, forest cover, TRIM, and fish habitat maps from government agencies.

INTRODUCTION

The Greater Vancouver Regional District has seen an unprecedented growth - a growth that has resulted in urban sprawls from the major cities to the growing municipalities and districts closer to the Fraser Valley and towards the slopes. An inevitable consequence of development getting pushed to the slopes, and to the valley, is land use change, which in turn translates into reduced water quality if the water sources are not protected. One of the ways governments address this issue is through the adoption and enforcement of buffer ordinances along water courses, the science behind which is well understood, yet adoption and enforcement lags behind. Buffer ordinances are basically regulations based on the assignment of buffer widths, and of the two approaches in assigning buffer widths, agencies go for the minimum fixed width buffer which is easier to implement, rather than to variable-width buffer, which, really has the greater potential of protecting the water.

This study shows that variable-width buffer from a GIS model has a place in the effort of regulatory agencies to continue protecting the quality of surface water. The goal of the study is to construct a GIS model that will find a variable-width buffer around surface waters in the lower Fraser river watershed that will protect water quality. Objectives include determining the relationships between land use classes and water quality in the Coquitlam, Pitt-Aloutte, and Kanaka watersheds through GIS and statistical analyses; the construction of a GIS model that will identify a variable width buffer based on relationships identified by employing ArcGIS Desktop Modeler and ArcGIS Desktop v. 9.1 tools; and evaluate the model in the Kanaka creek watershed.

REVIEW OF LITERATURE

The buffer tool is one of the most popular tools in GIS projects. In fact, it is very basic that even simple web servers now include buffering as an available functionality for simple browser clients. As a decision making tool, buffering is widely used by local governments, usually to restrict certain land-uses along water courses to protect water quality. Technically, buffering is a very simple process, a certain distance or width is selected and a buffer zone is created based on this distance. However, in terms of administration, governments are still grappling with issues of design and enforcement. This literature review looks at the issue of buffering in terms of design, specifically, in deciding between a fixed-width buffer (FWB) and a variable-width buffer (VWB).

PROTECTING WATER QUALITY THROUGH BUFFERS. Belt et al. (1992), IEUG (2000), Wenger and Fowler (2000), among other authors are in agreement that stream buffers when left undisturbed help protect water quality by trapping and removing contaminants, nutrients and sediment from runoff, stabilizing stream banks and reducing channel erosion, and by storing flood waters. However, the ability of the buffer strip to provide these functions depends on several factors as indicated in the following table.

*TABLE 1. FACTORS THAT AFFECT THE ABILITY OF BUFFERS TO PROTECT WATER QUALITY **

Factors		
Intrinsic	Physical	Ecological
Buffer Width	Soil type	Vegetation structure
Buffer Length	Slope	Growth rate of vegetation
Degree of fragmentation	Floodplain width	Density of vegetation
Buffer's position in the watershed	Valley floor morphology	Presence of wetlands

*Sources: Fischer and Fischenich (2000), Lee et al. (2003), Wenger and Fowler (2000)

Establishing the Buffer Width. The focus of buffer design is to address the width, rarely the length. The literature review resulted in a wide range of buffer widths, reflecting the range of specific study conditions from which the recommended values have resulted from. Fischer and Fischenich (2000) provided a summary of recommended widths for various water quality considerations from their extensive literature review. The width *per se* is not an issue, but application of a specific width to different sites is. The approaches in establishing buffer widths in the literatures reviewed fall into two types – the FWB and the VWB. Belt et al. (1992) reported in their analysis of more than 300 scientific papers related to forest riparian buffer strips for the protection of water quality that the only advantage minimum FWB have over VWB is that it is easier to implement and administer.

Buffer Strip Design Models. A number of models describing individual buffer strip functions were found in the literature. There is a predominance of models that relate buffer width and stream temperatures such as the prescribed buffer widths to control solar radiation described by Lee et al. (2003). The ability of buffers to reduce pollution from surface runoff is of interest to the current study, and among the most interesting models in this category is the model developed in Florida to protect water quality of the Suwannee River, from urban development, as discussed by Potts and Bai (1989). The model determines the width of a buffer for a given soil type, slope, vegetative condition, and amount of impervious surface. Lee et al. (2003) also described several models for determining buffer width for pollution mitigation based on slope, stream width and volume, buffer forest height and density, and land-use.

Buffer Width Adoption and Enforcement. The most interesting issue that came out of the literature review is concerned with the use of buffers as a regulatory tool. No matter how scientists show the importance of buffers, eventually, it is the ability of any regulatory agency to enforce buffer regulations that will count most, regardless of the specific value the buffer is protecting. From the reviewed literature, it is evident that the popularity of fixed-width buffers stems from the fact that they are easy to enforce and administer.

Local governments usually adopt, recommend, or enforce a buffer width that resulted from research institutions or from upper levels of government, and their goal as local managers, is to match or exceed this width (Lee et al. 2003). Millar et al. (1997) reported that a number of local governments and agencies throughout coastal British Columbia failed in their attempt to establish Fisheries Sensitive Zones based on guidelines that required a minimum 15 – 30 meter fixed-width buffer, indicating that adopting buffer widths may be easy, but enforcing buffer ordinances may be difficult. And if governments do not enforce what they adopt, the government may be held liable. For example, a copy of Petition No. 49 was published online by the Office of the Attorney General of Canada (2002). The petition concerned the protection of fish habitat through the Forestry Practices Code of British Columbia. The petitioner alleged that the government authorities have not enforced the provisions of the Fisheries Act and policies on 30 m buffer zones along small and feeder streams.

There is agreement in literature that buffer zones are important in protecting stream water quality and that governments adopt the FWB approach to determine buffer width because it is easier to implement. Among the gaps that I identified include the issue of cumulative effects and the lack of VWB studies in British Columbia. I believe that GIS can be used to demonstrate the effectiveness of using VWB to integrate several factors affecting the ability of buffers to protect water quality. GIS can also be the perfect integrating tool for multiple criteria expressed in spatial terms.

STUDY AREA

The study area is composed of three watersheds whose streams feed the Fraser River from the north, immediately before it reaches the ocean. These rivers are the Coquitlam, Pitt, and Aloutte rivers and the Kanaka creek, and their watershed boundaries are shown in *FIGURE 1*. The predominant land cover for most of this area is forest and all of the watersheds contain within them considerable fresh water lakes - potential sources of fresh water for a growing Lower Mainland population. Non-point sources of pollution would be an issue in the near future as the lower portions of the watershed have seen development at rates that have never been seen before in the Cities of Coquitlam and Port Coquitlam, as well as the Districts of Pitt Meadows and Maple Ridge. This region collectively absorbs the urban sprawl overflows from Vancouver. *FIGURE 2* shows the portions of the watersheds within the jurisdiction of the different local governments.

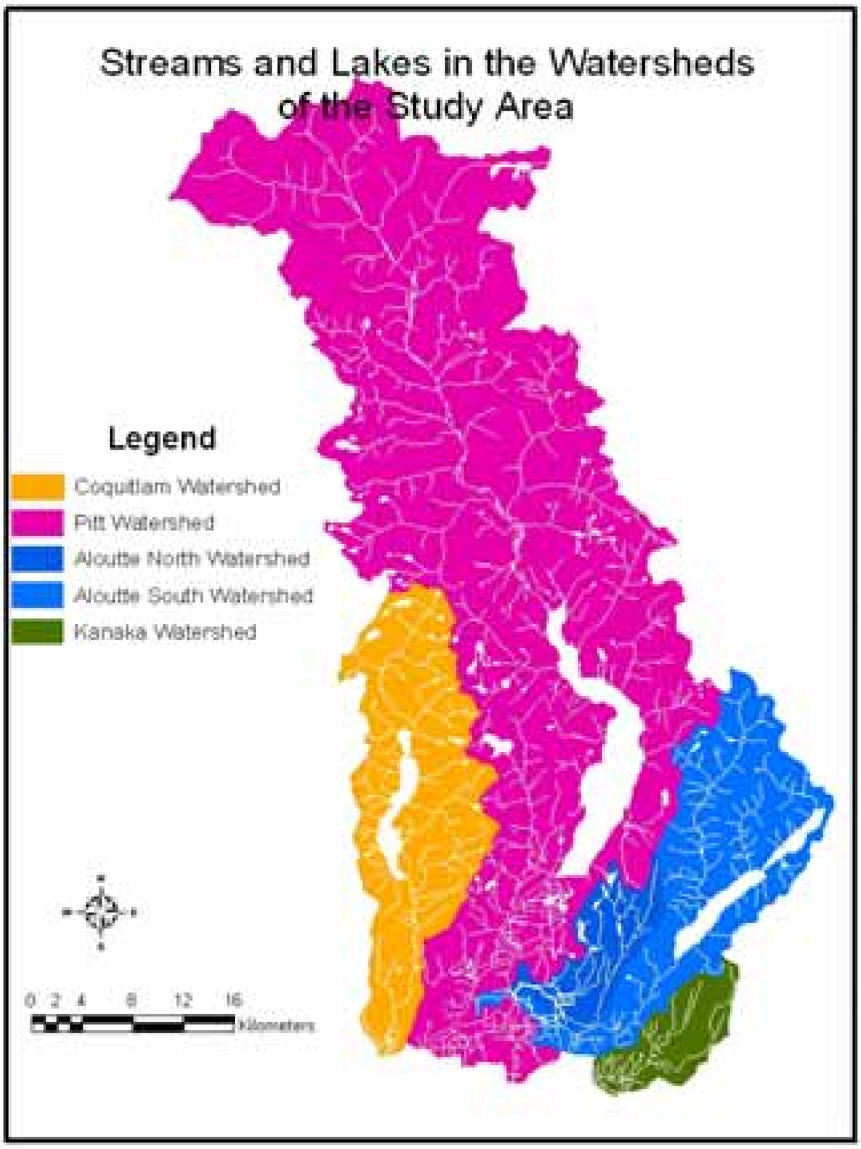

Figure 1. Water features in the study area

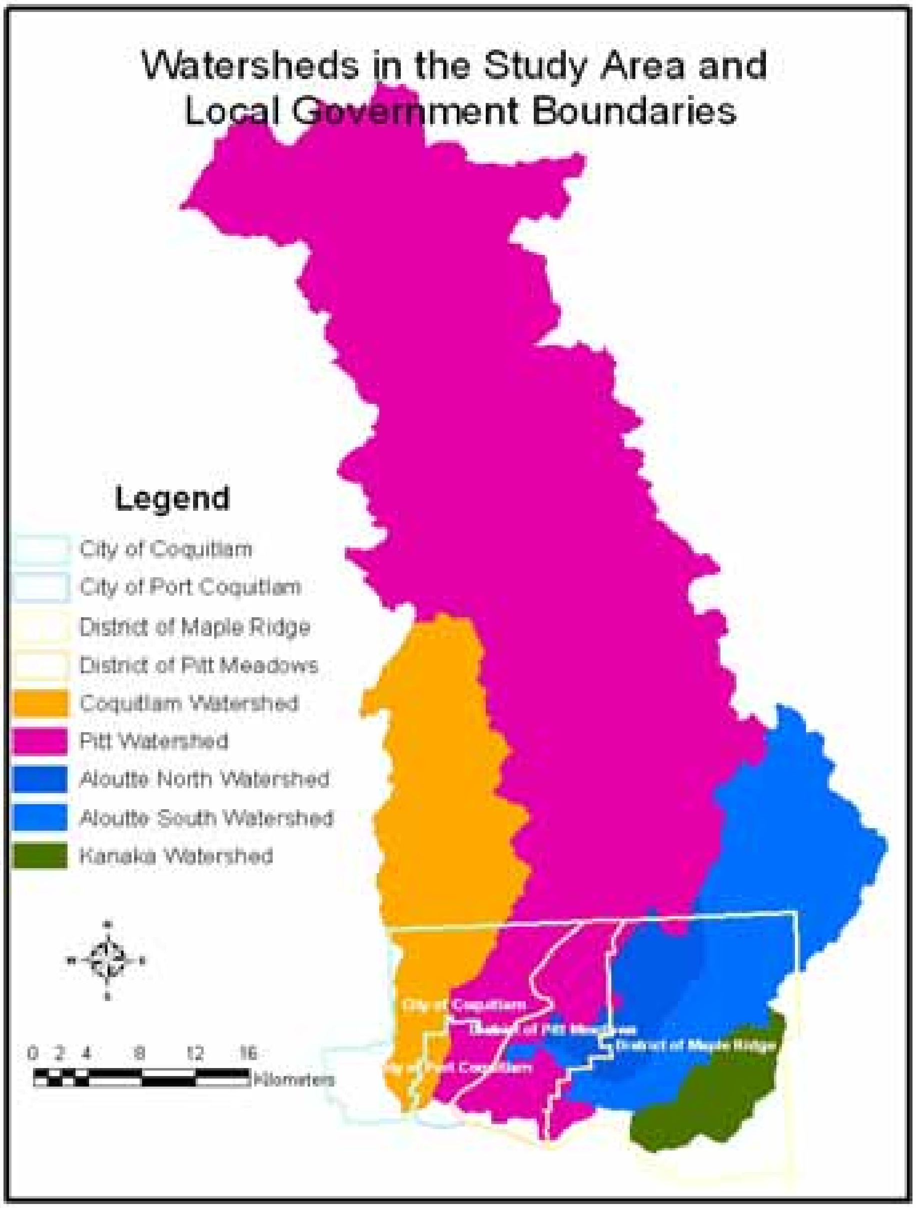

FIGURE 2. LOCAL GOVERNMENT BOUNDARIES IN THE STUDY AREA

MATERIALS AND METHODS

To standardise the data coming from different sources in different formats (*TABLE 2*), I decided to use ESRI shapefile and NAD 1983 Albers as the project standard format and projection. All the spatial data were converted to shapefiles and projected to NAD 1983 Albers. There were instances when tables or other features (*TABLE 3*) were joined to shapefiles before the shapefiles could be used. For instance, because the soils shapefile did not contain the drainage attribute, I had to join a table which I created in Excel from a hard copy material. When the forest cover polygon shapefile did not contain the required attributes, it was joined with the point feature class which contained it.

Joining map sheets to cover a watershed area, clipping the joined maps and recalculating areas were followed as standard operating procedures throughout the project. Special data manipulations carried out in the project before the construction of the variable width buffer model include the following:

Conversion of DEM to slope classes. The DEM files were converted to slope using the slope tool of the Spatial Analyst extension of the ArcGIS Desktop. This was followed by using the extension's slice tool to reclassify the created raster cells using natural breaks in the value distribution to group the data into 9 divisions.

Creation of point feature class out of tabular data. Water quality data were downloaded using the sponsor's access to the Ministry of Environment's water quality database. The data for each sampling station were converted to shapefiles using the geographic coordinates in the table as X and Y coordinates.

GIS analysis (buffer overlay). In order to study the different variables to be used in the construction of the model, these variables were extracted and studied in terms of 30-m buffer slices of the watershed with the water features (stream and lakes) as the origin. *FIGURE 3* shows a schematic diagram of the procedure.

Statistical analysis. Basic statistical analyses on each feature attribute by zone and correlation analysis of the attributes with water quality were carried out. MINITAB Release 14 was the statistical package used.

TABLE 2. DATA SETS FOR THE PROJECT

Data Set	Purpose	Projection	Source	Data Format
Water Atlas BC Min. of Env't	Streams Lakes Watershed boundaries	NAD83 Albers	Sponsor	(Digital) ArcINFO coverage
Land Use Map GVRD	Land Use 1996 Land Use 2001	NAD 83 UTM Zone 10	Sponsor	(Digital) ArcINFO coverage
Soils Map BC Min. of Agri. & Food	Soil type	NAD 83 UTM Zone 10	Sponsor	(Digital) ArcINFO coverage
Soils Bulletin 20 BC Min. of Agri. & Food	Soil Drainage	N/A	Sponsor	(Hard Copy)
VRI Map BC Min. of Env't	Forest Cover	NAD 27 UTM Zone 10	Maple Ridge Planning Dept.	(Digital) ArcINFO coverage
TRIM BC Min. of Env't	DEM points Cultural Points Land Cover	NAD83 UTM Zone 10	Sponsor	(Digital) Shapefile
Fish Habitat Map DFO	Presence of protected fish	NAD83 Albers	DFO site download	(Digital) Shapefile
Weather Data Env't Canada	Precipitation & Stream Discharge	N/A	EC site download	(Digital) Tabular data
Water Quality BC Min. of Env't	Water Quality Data	N/A	ME site download	(Digital) Tabular data

TABLE 3. DATA DICTIONARY FOR THE PROJECT

Layer Name	Feature Class	Attributes	Value	Description
Streams	Line	Name Order	Gazetted name 1, 2, 3, or 4	All types of streams Order based on position in watershed
Lakes	Polygon	Name	Gazetted name	All types of streams
Watershed Boundaries	Polygon	Area	Actual value	Delineated boundary
Land Use 1996 and Land Use 2001	Polygon	LU Code	A500 F100 M300 R100 S110 S120 S130 S300 S400 S500 U100	Agriculture Harvesting/Research Extraction Parks Simple Residential Rural Residential Low Rise Industrial Institutional Transportation Open

Soils	Polygon	AverageSoil Drainage	1.5 2.0 2.5 3.0 4.0 5.0 6.0 6.5 7.0	very rapid Moderately fast fast neutral to fast neutral neutral to poor poor moderately poor very poor
Forest Cover	Polygon	Soil nutrition	A B C D E	high moderately high good moderately poor poor
Cultural Points	Points	Type	Barn Beacon Building Church Fire Station Greenhouse Control Point Penitentiary Photo Centre Pier or Wharf Post Office School Silo Tank Transmission Tower	As described in the value
Land Cover	Polygon	Area	Actual value	woodlands
Chinook	Line	Presence	Present Not Present	Stream is fish habitat Stream not fish habitat
Chum	Line	Presence	Present Not Present	Stream is fish habitat Stream not fish habitat
Coho	Line	Presence	Present Not Present	Stream is fish habitat Stream not fish habitat
Cutthroat	Line	Presence	Present Not Present	Stream is fish habitat Stream not fish habitat
Pink	Line	Presence	Present Not Present	Stream is fish habitat Stream not fish habitat
Sockeye	Line	Presence	Present Not Present	Stream is fish habitat Stream not fish habitat
Steelhead	Line	Presence	Present Not Present	Stream is fish habitat Stream not fish habitat
Water Quality	Point	Ammonia Coliform DO *E. coli* *Enterococci*	Actual values	Grab samples from different years

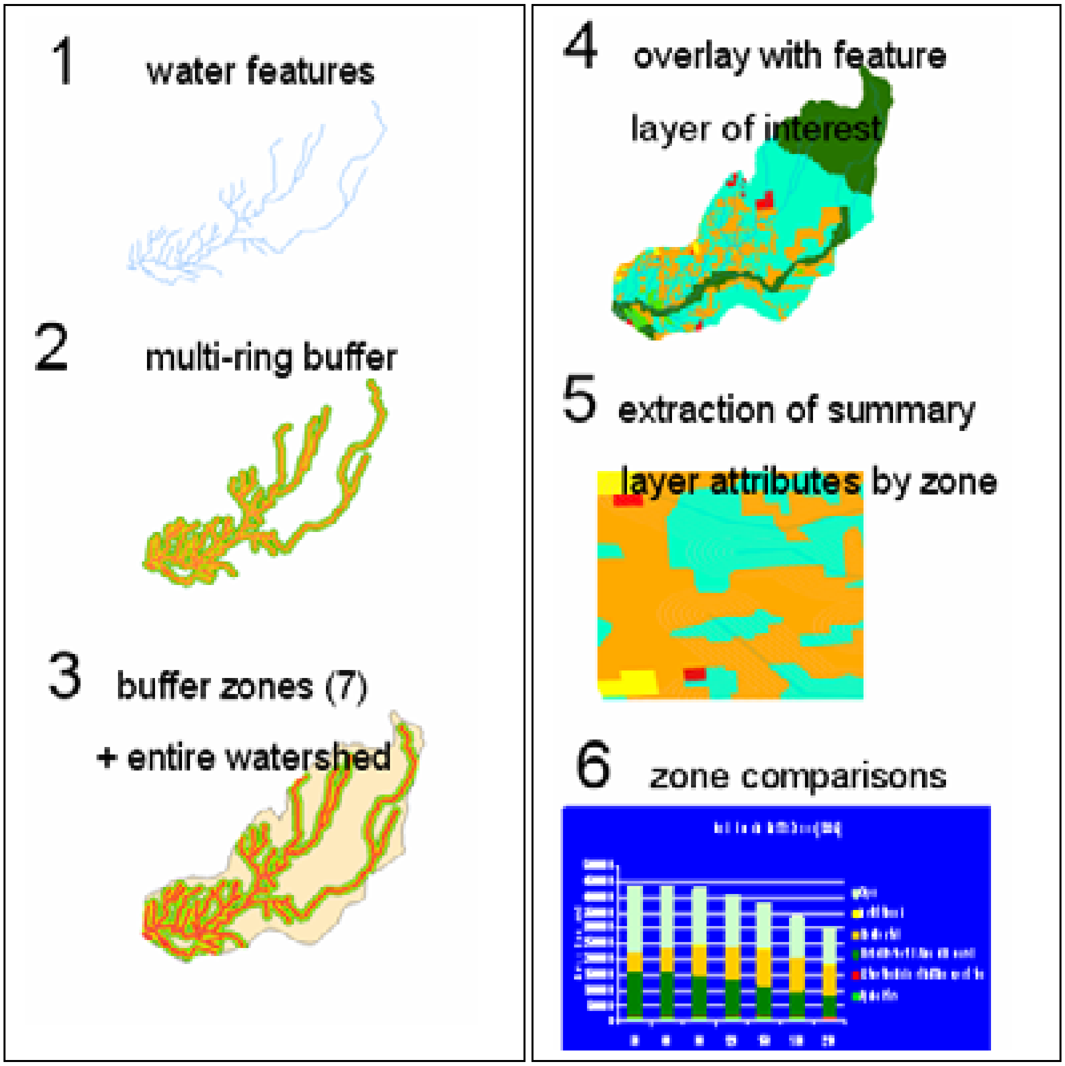

FIGURE 3. SCHEMATIC DIAGRAM OF GIS ANALYSIS USED IN THE PROJECT

RESULTS AND DISCUSSION

The Variable Width Buffer Model. The Variable Width Buffer (VWB) model was constructed in ArcGIS Modeler of the ArcGIS Desktop. The model, which can be run from ArcCatalog, has been saved using relative paths so it can be run on any computer with ESRI license. The model consists of four parts as shown in *FIGURE 4*. A pollution contribution surface was calculated in the first part while a pollution sink surface was calculated in the second part. The third part calculated the net pollution risk cost surface and a risk cost distance calculation using the stream as the origin outward to the watershed boundary. The last part integrated buffers that are legislated or recommended for fish habitat protection.

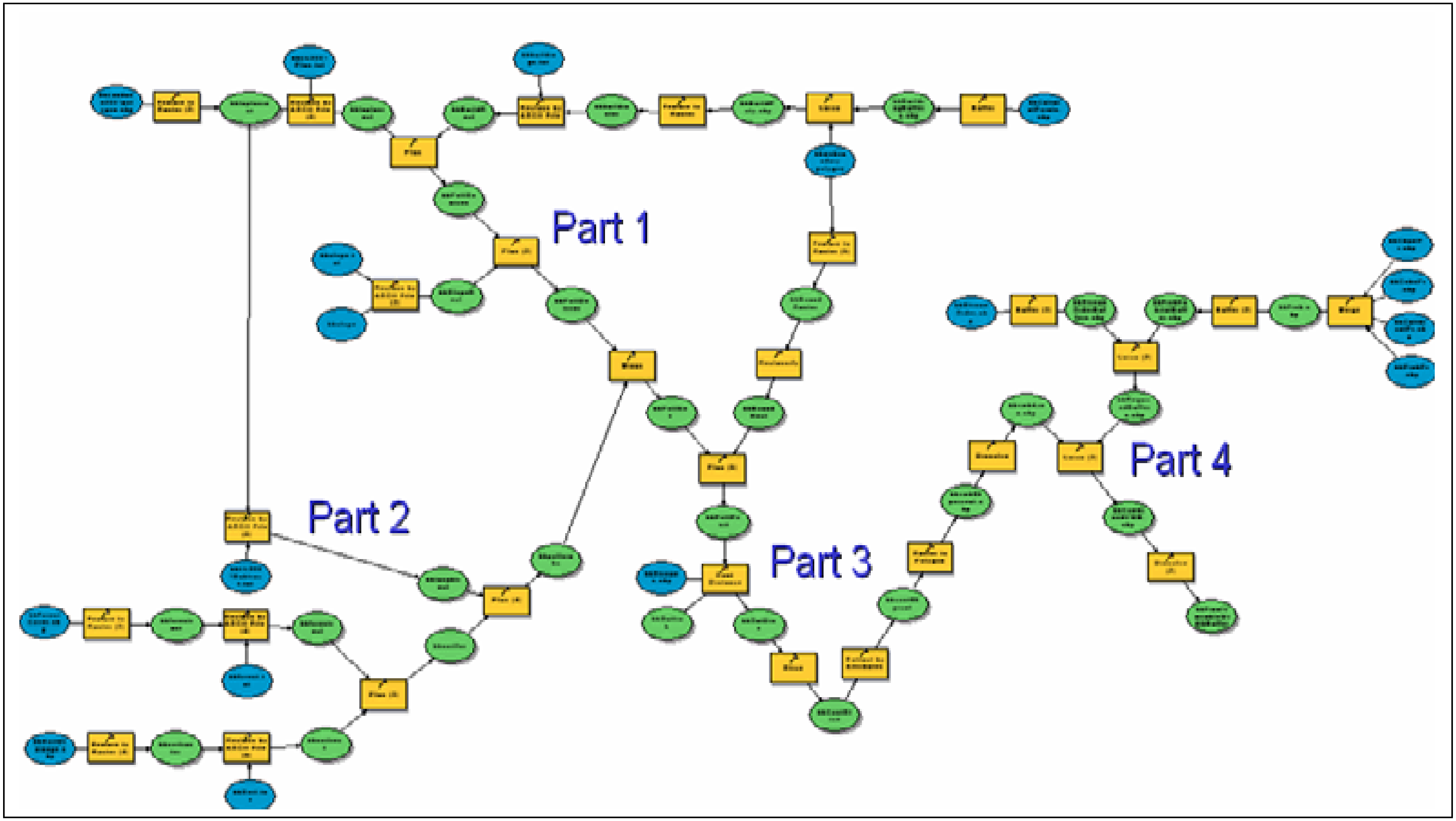

FIGURE 4. VARIABLE WIDTH BUFFER MODEL FOR THE KANAKA CREEK

The first step in the modeling process was the conversion of features to raster to allow the employment of raster arithmetic on the spatial data. This was followed by reclassification of raster values using relationships determined through the GIS and statistical analyses carried out previous to the construction of the model. After raster arithmetic processes that calculated a variable width buffer were carried out, raster surfaces were converted back to features.

PART 1: THE POLLUTION CONTRIBUTION SURFACE. The steps in the first part of the model were isolated from the whole model and are presented in *FIGURE 5*. From the upper left hand corner, it can be observed that the Land Use 2001 polygons were converted to raster and raster cell values were reclassed using *TABLE 4* so land uses that were found to be pollutant sources such as extraction, transportation and open lands were assigned positive integers while the other land uses are assigned zero values.

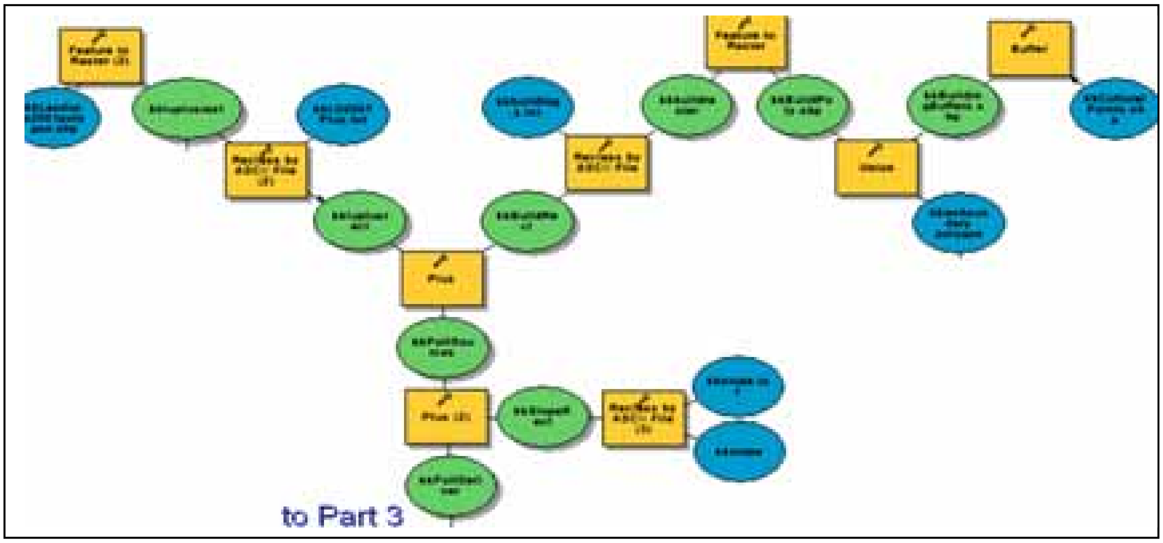

FIGURE 5. VARIABLE WIDTH BUFFER MODEL PART 1: POLLUTION CONTRIBUTION SURFACE

TABLE 4. RECLASS TABLE FOR LAND USE AS SOURCES OF POLLUTION

Land Use Code	Description	Assigned Value
A500	Agriculture	0
F100,R200	Parks, Watershed	0
M300,S300,S500	Extraction, transportation, industrial	8
S120,S110,S130	Residential	4
S200,S400	Commercial, institutional	4
U100	Open Areas	0

The buffering of the cultural points feature class by 18 m to come up with an average 1000 sq. m area for each feature is shown in the upper right hand corner of *FIGURE 5*. This was followed by overlaying the building polygon feature class with the watershed boundary in order for the feature class to be able to cover the whole watershed area. The resulting feature class was converted to raster and reclassed using *TABLE 5*. This assigns higher values to structures that are highly likely to contribute to pollution and give the ones without building structures a value of zero. The reclassed pollution sources are added together to form the sources of pollution surface.

TABLE 5. RECLASS (PLUS) TABLE FOR CULTURAL STRUCTURES AS SOURCES OF POLLUTION

Type	Assigned Value
Building	2
Church	4
Photo Centre	0
Silo	8

The slope raster which was created from the DEM and reclassed using natural breaks in the slope surface was further reclassed using *TABLE 6* to take into consideration the effect of slope in the delivery of pollutants to the stream. The reclassed slope surface was added to the pollution sources surface to form the pollution contribution raster surface which was later on joined to Part 3 of the model. The resulting pollution contribution surface shown in *FIGURE 6* reveals that the steep slopes as well as the areas with high building density or residential areas obtained higher values.

TABLE 6. RECLASS TABLE FOR SLOPE AS A FACTOR IN DELIVERING POLLUTION TO A STREAM

Slope (Degree)	Assigned Value	Assigned Value
0 – 2.79	1	0
2.79 – 5.57	2	1
5.57 – 8.36	3	2
8.36 – 11.15	4	3
11.15 – 14.11	5	4
14.11 – 17.41	6	5
17.41 – 21.41	7	6
21.42 – 27.00	8	7
27.00 – 44.41	9	8

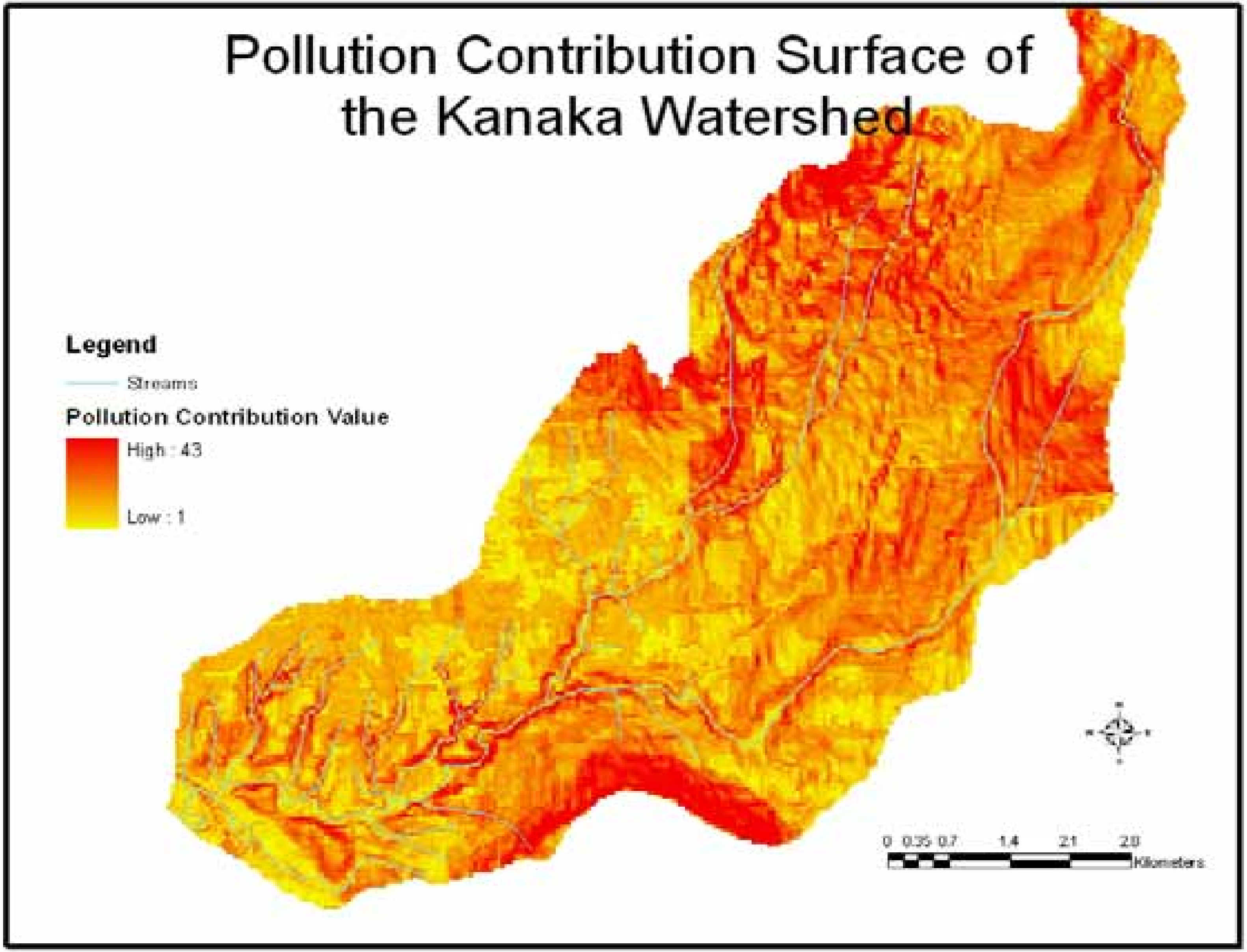

FIGURE 6. POLLUTION CONTRIBUTION SURFACE OF THE KANAKA WATERSHED

PART 2: THE POLLUTION SINK SURFACE. The isolated Part 2 of the model is shown in *FIGURE 7* where the three variables used to calculate the pollution sink surface are shown. The land use raster generated in Part 1 was used a second time. A second reclass table (*TABLE 7*) was used to reflect the results of statistical analysis which revealed that some land uses were pollution sinks.

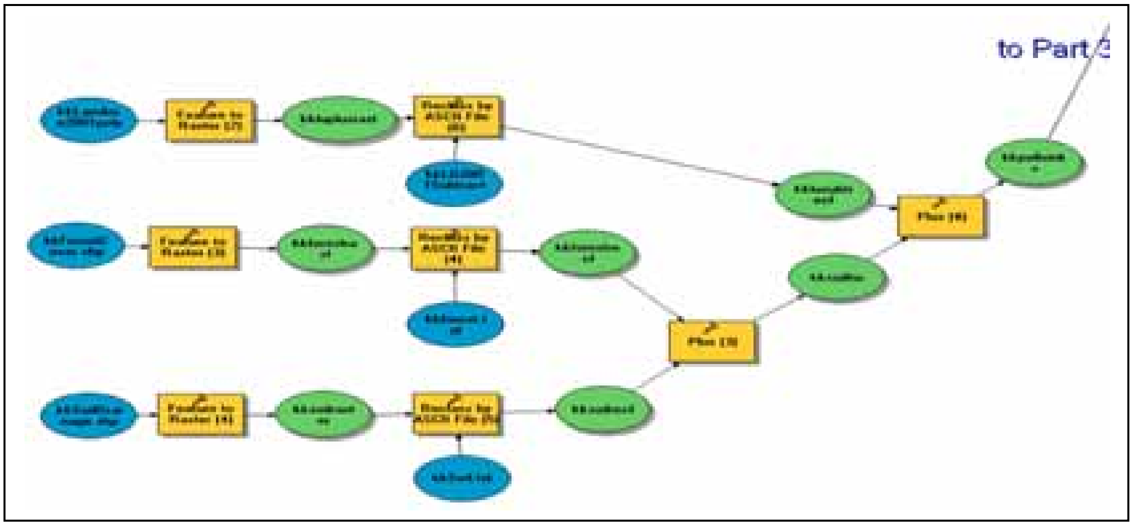

FIGURE 7. VARIABLE WIDTH BUFFER MODEL PART 2: POLLUTION SINK SURFACE

TABLE 7. RECLASS (SUBTRACT) TABLE FOR LAND USE AS SOURCES OF POLLUTION

Land Use Code	Description	Assigned Value
A500	Agriculture	4
F100,R200	Parks, Watershed	8
M300,S300,S500	Extraction, transportation, industrial	0
S120,S110,S130	Residential	0
S200,S400	Commercial, institutional	0
U100	Open Areas	8

The forest cover polygon feature class was converted to raster and reclassed using the soil nutrition attribute as a surrogate for the density and growth rate of the forest vegetation. The reclass values used for the raster surface are indicated in *TABLE 8*.

TABLE 8. RECLASS TABLE FOR FOREST COVER AS SINKS FOR POLLUTION

Forest Cover Soil Nutrition Code	Assigned Value
A	8
B	6
C	4
D	2
E	1

The soil polygon feature class was converted to raster and cell values were reclassed according to drainage attribute as shown in *TABLE 9,* with well drained sites as better sinks for pollutants. The three reclassed raster surfaces were combined to become the pollution sink surface. As can be seen in *FIGURE 8*, the main stem of the Kanaka creek as well as the heavily forested headwaters were extremely good pollution sinks.

TABLE 9. RECLASS TABLE FOR SOILS AS SINKS FOR POLLUTION USING THE SOIL DRAINAGE ATTRIBUTE

Soil Drainage Average	Assigned Value
1.50	8
2.00	7
2.50	6
3.00	5
4.00	5
5.00	4
6.00	3
6.50	2
7.00	1

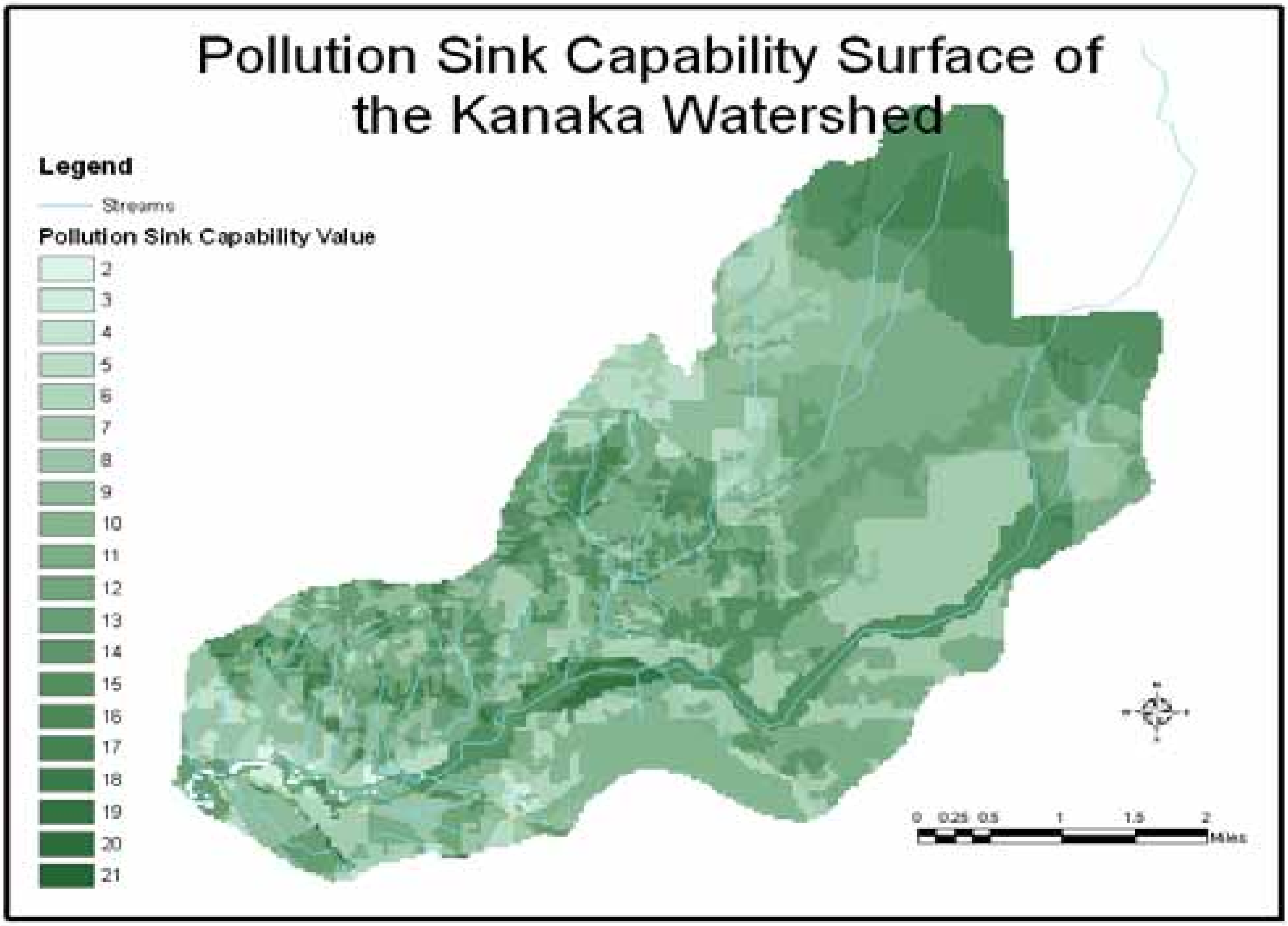

FIGURE 8. POLLUTION SINK SURFACE OF THE KANAKA WATERSHED

PART 3: THE POLLUTION RISK COST SURFACE. From the pollution sources surface was deducted the pollution sink surface to determine the net pollution risk for the watershed as shown in *FIGURE 9*. The watershed boundary was converted to raster and reclassed using a value to adjust the net pollution risk surface to positive integers, since the Cost Distance tool of the Spatial Analyst extension does not support surfaces with negative values.

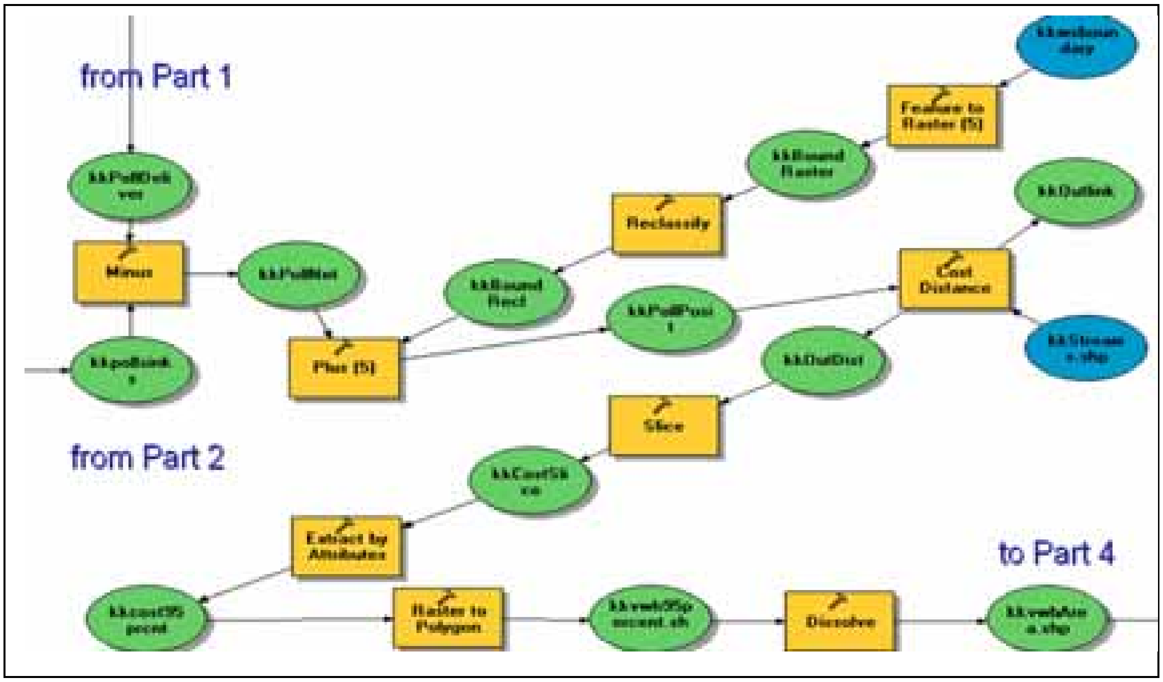

FIGURE 9. VARIABLE WIDTH BUFFER MODEL PART 3: POLLUTION RISK COST SURFACE

The positive net pollution surface was used to calculate the cost distance from the stream to the watershed boundary and the resulting outdistance was sliced to 100 portions using natural breaks in the surface value distribution. The values in the 95th percentile were then extracted and converted into polygons and their boundaries dissolved resulting in a variable width buffer area for the Kanaka creek watershed as shown in *FIGURES 10* and *11*.

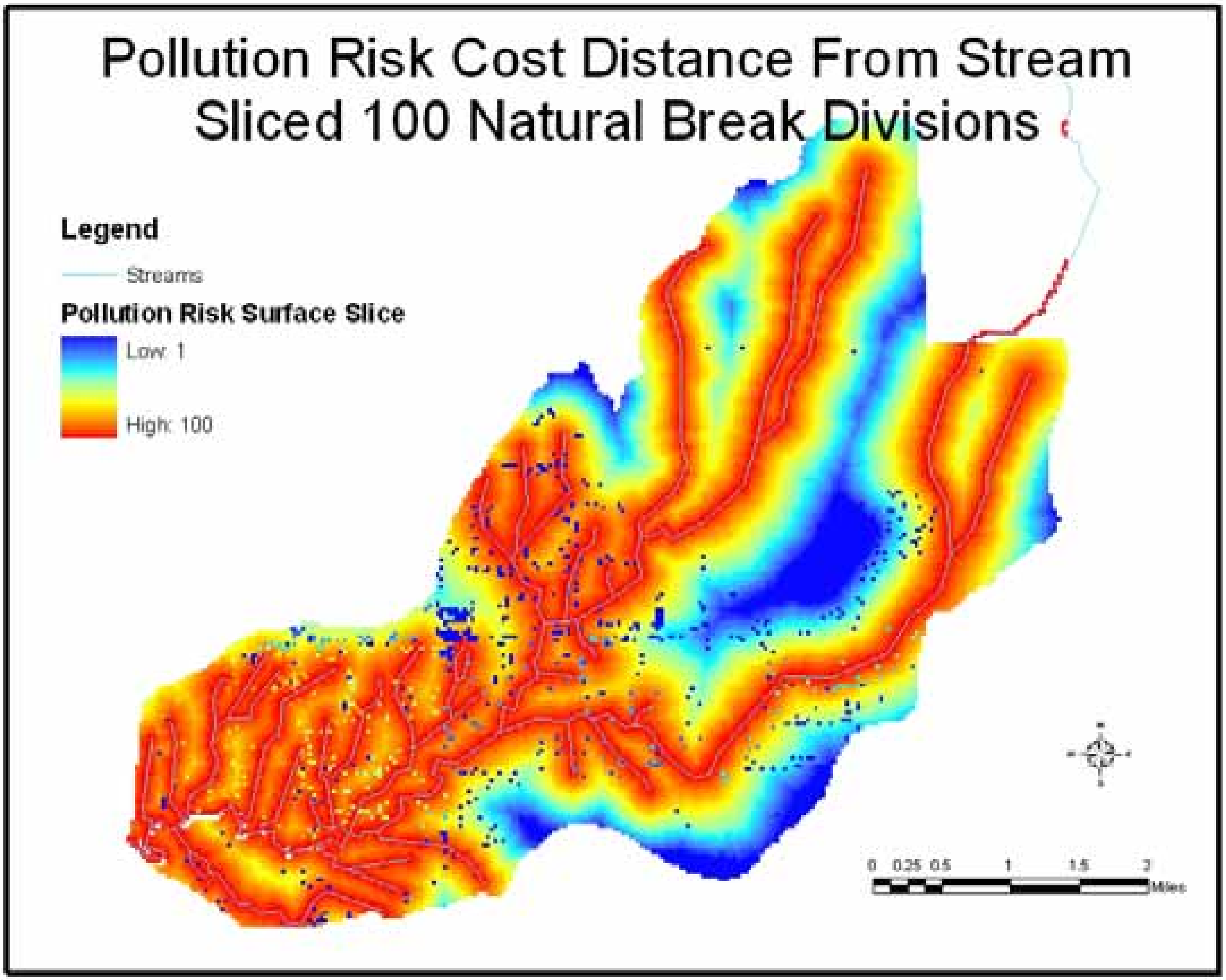

FIGURE 10. POLLUTION RISK COST DISTANCE FROM THE STREAM SLICED 100 TIMES

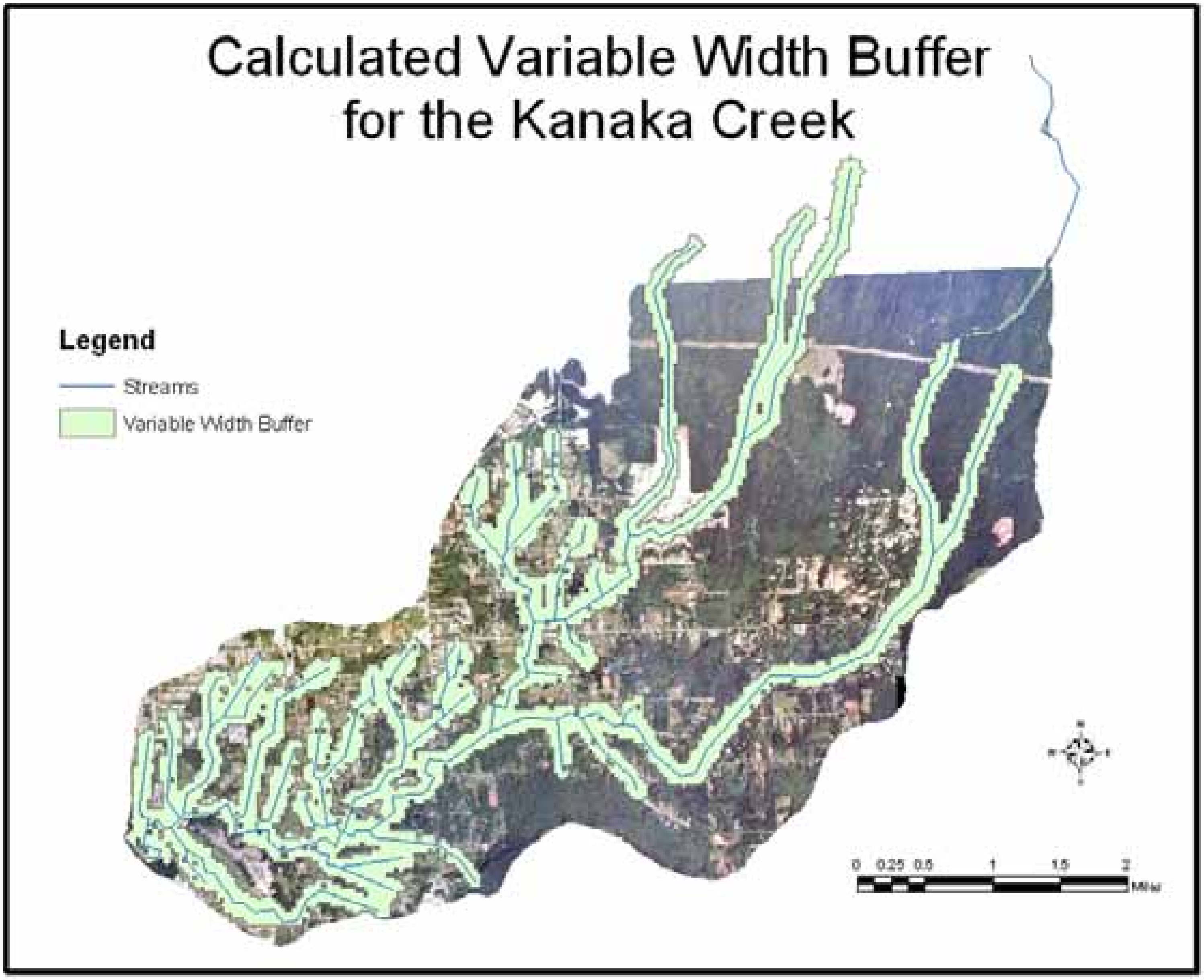

FIGURE 11. VARIABLE WIDTH BUFFER FOR THE KANAKA CREEK FROM POLLUTION RISK COST DISTANCE

PART 4: INTEGRATION OF OTHER BUFFERS. Current buffer regulations in the province and buffer recommendations found in literature were integrated into the calculated variable width buffer in *FIGURE 12*. From the upper right, the streams were buffered based on stream order as indicated in *TABLE 10*. Literatures reviewed suggested that headwaters should be offered the most protection.

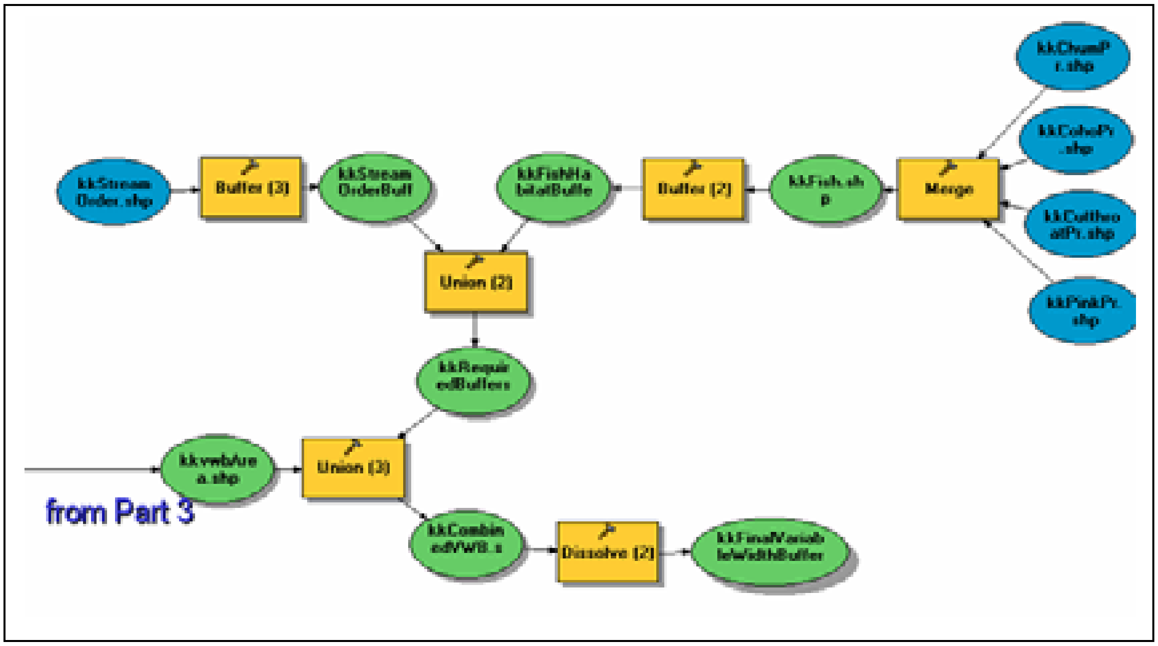

FIGURE 12. VARIABLE WIDTH BUFFER MODEL PART 4: INTEGRATION OF OTHER BUFFERS

TABLE 10. BUFFER DISTANCES USED FOR EACH STREAM ORDER

Stream order	Buffer Distance (m)
1 (Headwaters)	54
2	46
3	38
4	30

Four protected fish species were present in the Kanaka creek so the portions of the creek where these fishes were present were buffered by 60 m. The resulting buffers were all overlaid to reflect an overall fish habitat buffer. The fish habitat buffer was overlaid with the stream buffer where the stream order was used and the two buffers were overlaid together to come up with the feature class on required buffers. When the required buffer feature class was overlaid with the calculated variable width buffer area, the final variable width buffer for the watershed was produced. The different buffers presented in *FIGURE 13* protect the headwaters as well as the fish habitat in the Kanaka creek watershed.

CONCLUSION AND RECOMMENDATIONS

A variable width buffer model was successfully constructed based on land-use water quality relationships that were determined through ArcGIS and statistical analyses of readily available maps of variables that influence a buffer's ability to protect surface water from pollution.

There are several opportunities in fine-tuning the model. First is in the area of pixel resolution when converting the different feature classes to raster surfaces. In constructing the model, the pixel sizes suggested by ArcGIS (default) were used. I abandoned the use of a single pixel size of 10 m which I followed in the trial stage of the model construction as a compromise between the lowest pixel size of 5 m and the highest pixel size of 40 m, since raster processing using available workstations became slow.

The model made use of variables from readily-available maps but there may be other maps where other variables can be extracted and used in the construction of the model. Finally, it is recommended that the model be evaluated also on other watersheds in the area.

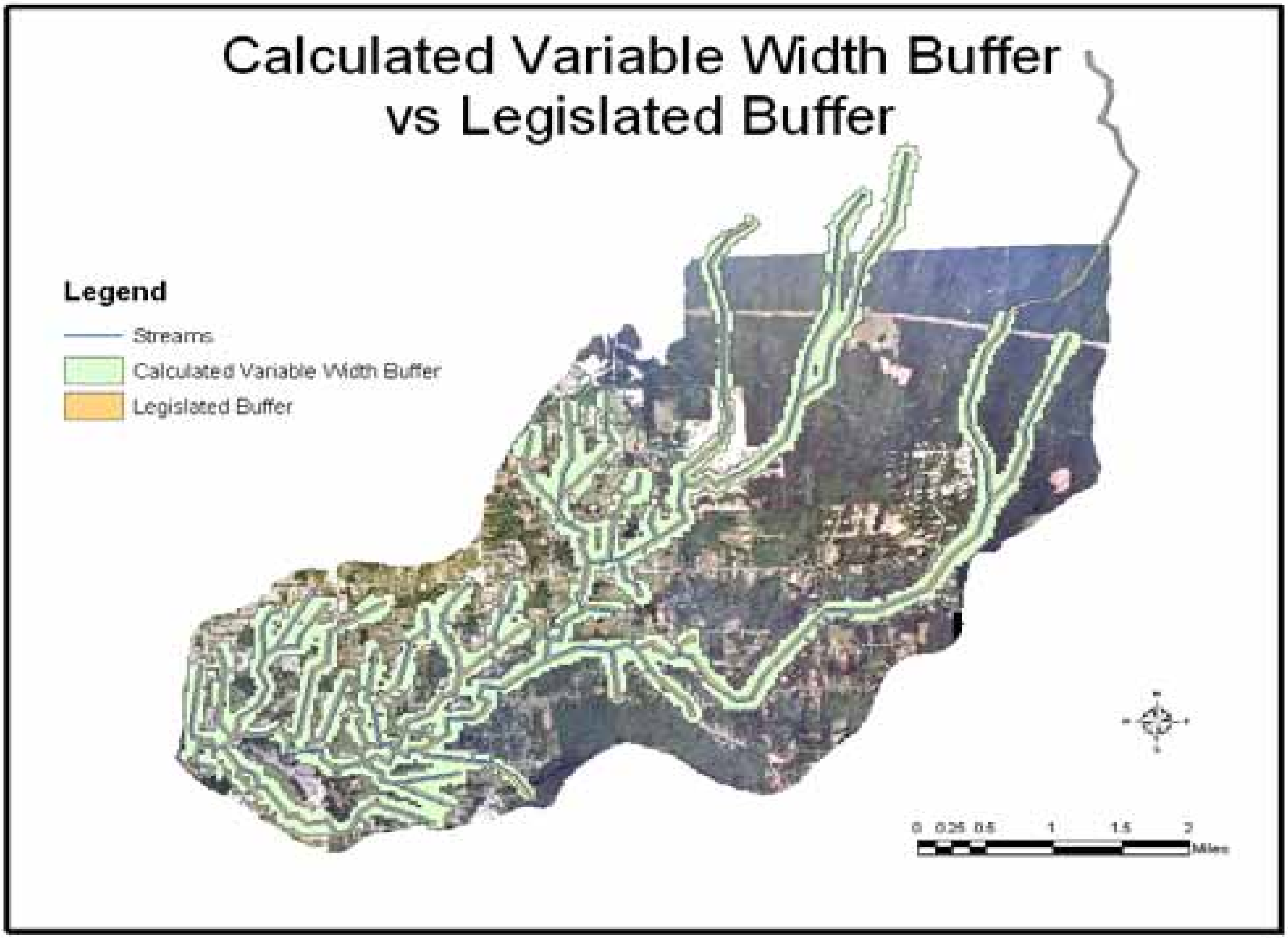

FIGURE 13. CALCULATED VARIABLE WIDTH BUFFER FOR THE KANAKA CREEK AND OTHER BUFFERS

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