GEOSPATIAL MODELING OF FOREST ROAD NETWORKS AND THEIR EFFECTS ON STREAM MACROINVERTEBRATE COMMUNITIES

Aaron M. Bernard, Stephen P. Prisley, W. Michael Aust
Department of Forestry, Virginia Tech, Blacksburg, VA 24061

Conrad D. Heatwole
Biological Systems Engineering, Virginia Tech, Blacksburg, VA 24061

ABSTRACT

Road construction and maintenance throughout the country continues to be one of the largest contributors of sediment pollution to aquatic systems. Though impacts of road networks on aquatic systems can be potentially severe, little work has been performed to evaluate the effect that road spatial location within a watershed has on water quality. To address this issue from a quantitative perspective, a "Road Impact Factor" protocol was designed to identify potential erosion-prone segments of road networks based on road gradient, spatial location based on hydrologic flow length, surface composition, and water control installations. The protocol was developed for two regions in Central Idaho and Eastern Oregon. We then used the hydrologic travel time procedure, developed for use in the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) runoff and routing model, in order to characterize the spatial distribution of potential road runoff impacts within the study areas. Ten macroinvertebrate metrics sensitive to sedimentation (i.e. % Intolerant Taxa, Hilsenhoff Biotic Index, etc.) were analyzed to test the significance of the spatial distribution of Road Impact Factors. These 10 metrics were analyzed under the hypothesis that values will be lower for those study areas that have a higher degree of road impact and a lower distance between the road segments and stream reaches. Results of a quadrant analysis and hierarchical clustering analysis showed hypothesized trends for several metrics in Idaho, though the trends were not strong. No trends were observed in Oregon. The variability in results is likely due to limitations of the input datasets.

KEYWORDS. Geographic information systems, road impacts, benthic macroinvertebrates, sedimentation, hierarchical clustering analysis.

INTRODUCTION

The sustainability of aquatic biota and ecosystem health is directly linked to levels of pollutants entering the water. Due to these concerns, numerous rapid bioassessment protocols have been developed utilizing various media including periphyton, benthic macroinvertebrate communities, and fish assemblages (Barbour et al., 1999). The key to the effectiveness of these methods is that they allow for data analysis that has the ability to separate anthropogenic influence from ecological processes that represent natural, background, and reference conditions (Skinner,

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2003). These protocols offer a way to achieve subjective and repeatable measures of stream health impairment that can be compared consistently across regional and ecosystem gradients. Quantitative approaches are increasingly being promoted in order to accurately and consistently categorize the extent of stressor impacts. The Bureau of Land Management's (BLM) Aquatic Indicators of Land Conditions (AILC) program was created to investigate consistent monitoring approaches correlating stream macroinvertebrate community structure with land health across BLM lands (BLM, 2003). In conjunction with the multiple uses occurring simultaneously on BLM lands, including grazing, road construction, energy development, and timber production, a wide array of impacts on aquatic systems related to the intensity of these uses is possible. The nature of these impacts also varies in relation to the spatial context of the uses on the landscape. In order to fully characterize the impact that land use has on a watershed, aquatic macroinvertebrate assessment protocols must be paired with a characterization of the stressor structure on the landscape, or little will be known except that one watershed appears to be more impaired than another based solely on comparative macroinvertebrate metrics.

The need for effective biomonitoring techniques that utilize biological organisms diverse enough in their response to stressors to indicate trends in land uses is crucial for the implementation of effective remediation and planning efforts by land managers. Effective biomonitoring techniques must not only incorporate responses that are significantly sensitive to a range of stressor inputs, but must also be based on scientifically accepted, rigorous, and repeatable protocols that can be utilized across multiple scales of analysis. This concept corresponds with the AILC mission of procedural development that can be applied across BLM lands.

Aquatic macroinvertebrates offer many advantages in biomonitoring that can be useful in understanding the impact of land use on aquatic systems. First, the responses of many macroinvertebrate species to different types of pollutants are well established. Second, many methods of data analysis, such as biotic and diversity indices, have been developed and are widely implemented in community-level biomonitoring (Rosenberg and Resh, 1993). Third, qualitative sampling can be performed with simple, inexpensive equipment and in circumstances when time and personnel training are a constraint. Benthic macroinvertebrates have been utilized to achieve biomonitoring goals in a variety of ways, such as monitoring changes in genetic composition, bioaccumulation of toxicants, toxicological testing in the laboratory and field, and measurements of changes in population levels, community composition, and ecological functionality (Rosenberg and Resh, 1993).

Road construction and maintenance throughout the country continues to be one of the largest contributors of pollution to aquatic systems. Road systems often act as indicators for a variety of anthropogenic impacts. In other words, roads are more than just one of many impacting factors, because it is likely that an increase in road network density is accompanied by an increase in various other human impacts such as mining, urban development, timber harvesting and agriculture. Substances such as sediment, nutrients, petroleum-based products such as oil and gasoline, various engine fluids, and polycyclic aromatic hydrocarbons (PAH) leached from the asphalt on paved roads have adverse effects on many characteristics of water quality (Swift, 1984; Beasley and Kneale, 2002; Clinton and Vose, 2003). On federal lands, such as BLM, the majority of road pollutants are in the form of sediment originating from newly disturbed areas such as road cut and fill slopes, or from runoff caused by poorly designed, constructed, or maintained road segments. Sediment influx can alter the biological and morphological characteristics of stream systems including turbidity, temperature, dissolved oxygen, substrate composition, habitat alteration, fluctuations in peak flow, and alterations in food source composition for aquatic biota. The consequences of such alterations on aquatic macroinvertebrate habitats are potentially severe, and as such, protocols for assessing the degree of degradation and its correlation with road presence is of vital importance.

This study addresses an area of research that is currently underdeveloped by incorporating recent capabilities of integrating spatial and biological characteristics. Numerous government agencies and projects primarily oriented towards managing natural resources are using basic road density measurements as an attribute or preliminary screening tool for watersheds and other hydrologic management units that may be at risk (i.e. ICBEMP project). This technique only considers the total amount of road distance within a specified management area, which lacks any integration of impacts from the roads spatial location, interactions with the surrounding land characteristics, and distances to potentially vulnerable aquatic features.

When assessing potential impacts in this manner, the method(s) in which distance is measured becomes extremely important, given that distance is the primary factor utilized in assessing the impact extent for a particular road network. Innovations and improvements in distance measures, relevant to disciplines such as watershed hydrology (i.e. flow length and travel time) and transportation (i.e. least-cost pathways), have enhanced the concept of distance beyond a purely "straight-line" assumption, to one in which multiple interactions along a given pathway can be identified and accounted for (Heatwole and Burcher, 2003). The result is a more realistic model of the process under investigation.

Since these goals are in accordance with the mission of the AILC to develop a consistent monitoring program correlating stream macroinvertebrate community structure with land health across BLM lands, the objectives of this study have been defined as follows:

1. Develop a "Road Impact Factor" protocol designed to identify potential erosion-prone segments of road networks based on factors including road gradient, surface composition, and water control installations.
   - Many of these factors will be determined from ancillary data sources, as the road network data used in this study does not contain this information. This road network characterization is a crucial step, when coupled with various distance-to-watershed outlet measures, in relating road impacts to water quality concerns.
2. Determine if Road Impact Factor can be utilized to correctly categorize watershed water quality impacts by determining the spatial arrangement of road network impacts throughout the watershed.
   - Once a Road Impact Factor has been calculated for each road segment, factors relating runoff transport across the land surface from the road to the watershed outlet must be quantified. The surface flow modeling technique used in this study is hydrologic travel time to determine the effects observed in the macroinvertebrate sample points located at the outlet point of each study watershed.

METHODS

Study Sites and Macroinvertebrate Points

Selection of study sites was performed with respect to incorporating an adequate number of reference points in the respective 8-digit-HUCs and eliminating temporally redundant sample points. By implementing these criteria, 101 areas were selected as study sites for this project. Table 1 provides a summary of the total reference and non-reference points for the Oregon and Idaho study areas. Each study watershed was derived using an individual macroinvertebrate sample point as the watershed outlet. The Watershed tool in ArcGIS Desktop was utilized to derive the upstream watershed boundaries, therefore all potential impacts within the watershed could be correlated to the macroinvertebrate outlet point sample.

Table 1. Summary of total reference and non-reference study sites.

	OREGON	IDAHO
# HUCs	6	3
Reference	8	26
Non-Reference	41	26
Total	49	52

Reference sites must represent those areas that exhibit minimal anthropogenic impacts occurring as a result of road networks. These sites will act as a macroinvertebrate metric baseline for areas assumed to have minimal to no impact from road networks. National Wilderness Preservation Areas and U.S. Forest Service Roadless Areas were used as a template to identify reference points from the macroinvertebrate database. This seemed logical since these areas inherently contain very few roads and this template can be applied at the regional scale of this study. Through preliminary statistical analysis of the entire macroinvertebrate database, it was found that several commonly used metrics (i.e. abundance, EPT) had higher values at these designated reference sites when compared with non-reference sites.

Ten macroinvertebrate metrics were analyzed at each study site under the hypothesis that water quality will be worse in those watersheds that have higher Road Impact Factors, a shorter distance between the road segments and the watershed outlet, or a high combination of the two. Terms in Italic (Table 2) represent abbreviations used in analysis. Stream metric responses were taken from Kerans and Karr (1994).

Road Impact Factor (RIF) Protocol Development

Five central concepts that are typically associated with problematic road segments, in regards to sedimentation potential, were identified and incorporated in this protocol. The following five parameters were assessed and modeled in a GIS environment in order to facilitate the comparison of multiple stressors and potential impacts across multiple ecological regions.

1. Road spatial location in relation to stream reaches
2. Road gradient
3. Road surface type
4. Road water control features

Weighting factors based on the literature, shown in Table 3, were utilized for each factor in order to develop accumulative road impact factor for each road segment that corresponds to its sedimentation potential (Aruga et al. 2005).

Table 2. Metrics used in this study along with the expected response of each metric value to harmful stream impacts.

Metric Description	Expected Value Response to Disturbance
Ephemeroptera Taxa (*EPHET*)	Decrease
% Ephemeroptera (*%EPHEA*)	Decrease
Plecoptera Taxa (*PLECT*)	Decrease
Predator Taxa (*PRT*)	Decrease
% Shredders (*%SHA*)	Decrease
% Predators (*%PRA*)	Decrease
% Collectors/Filterers (*%PRA*)	Increase
Pollution Intolerant Taxa (*KINTT*)	Decrease
Hilsenhoff Biotic Index (*TV1*)	Increase
Tolerant Taxa (*KTOLT*)	Increase

Table 3. Soil sediment erosion factors for road impact parameters.

Parameter		Subelement	Factor
Road Slope		< 8%	0.20
		8-12 %	1.00
		> 12 %	2.50
Spatial Location		< 100 m from stream	1.00
		Between stream and ridge	0.35
		> 100 m from ridge	0.10
Road Class Code			
	Idaho (IDL)	5180	0.40
		1050	1.00
		5150	2.00
		960	0.50
		1060	1.00
		890	1.00
	Oregon (TIGER)	Class I (A41)	0.40
		Class II (A51)	1.00
		Class III (A74)	1.00

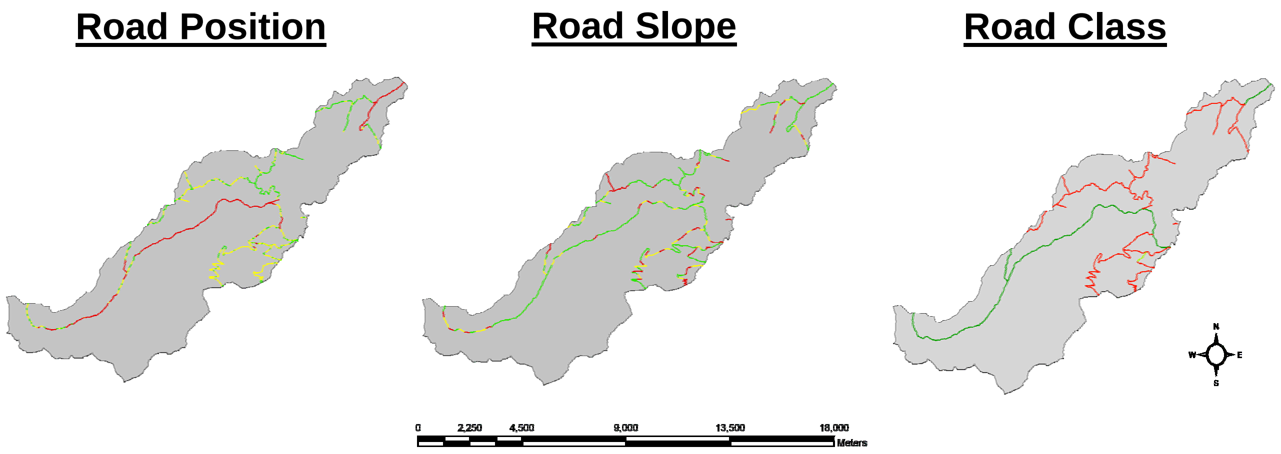
For each of the aforementioned road impact parameters, a separate road impact network was created (Figure 1). Segmentation for each road network was performed according to the particular parameter being modeled. Each segment also had an associated length attribute. A final road impact network was then created by intersecting the three individual parameter road impact networks. This process output one final road impact network, where the segmentation is based on unique combinations of the 3 input parameters, and the degree of impact for each unique segment was calculated based on a weighting corresponding to the lengths of the parameters and the associated weighting factor for the specific parameters shown in Figure 1 (Aruga et al., 2005).

Hydrologic Distance Parameter Development

To fully quantify the potential impacts of road segments on stream health, the spatial relationship between roads and streams must be determined. Though straight-line distances have been used in the past for stream health management, in the form of streamside management zones and other BMPs, this technique does not take into account the nature of water flow across the surface of the watershed. There is an increased need for hydrologically relevant distance measures that account for various watershed characteristics such as land cover, topographic variation, stream type and size, and precipitation magnitudes. The distance measurement utilized in this study was watershed travel time, which takes many of the aforementioned characteristics into account. Travel time is a portion of a Precipitation-Runoff-Routing distributed model used widely in the form of the HEC-HMS computer model developed by Army Corp of Engineers. By utilizing a set of runoff equations and multiple input parameters, a "time of travel" from each point in the watershed to the watershed outlet can be estimated. Travel time was used as a surrogate for distance in this study.

GIS-based distributed models, such as watershed travel time, use readily-available raster data to estimate flow distance and flow travel times throughout a watershed, without the need for actual gauged flow data (Heatwole and Burcher, 2003). The calculation of Travel Time incorporates four basic steps:

1. Partition each watershed into Sheet, Concentrated, and Channel flow. Sheet flow represents areas within 100m flow length from ridges (0 flow accumulation values). Concentrated flow represents areas between Sheet and Channel flow. Channel flow represents stream channels corresponding to intermittent and perennial streams on USGS topographic quadrangles. These channels were calculated using an 800 10-meter cell flow accumulation cutoff in Idaho and a 1200 10-meter cell flow accumulation cutoff in Oregon.
2. Calculate an inverse velocity grid (min/m) for each cell based on its assigned flow type (Step 1). Each partitioned area, representing Sheet, Concentrated, and Channel flow, has a particular inverse velocity formula associated with it.
3. Combine the three inverse velocity grids into a single grid according to the flow type a particular cell represents (Sheet, Concentrated, and Channel).
4. Calculate Travel Time for the entire watershed using the Flow Length tool in ArcGIS Desktop with the inverse velocity grid as a weight grid. Essentially, for each grid it calculates flow length (m) x weight grid (min/m) which results in a time grid (min) for each cell's travel time to the outlet point of the watershed.



Road Position Segments

Value	Description
0.1 🟩	Ridge
0.35 🟨	Midslope
1 🟥	Valley

Road Slope Segments

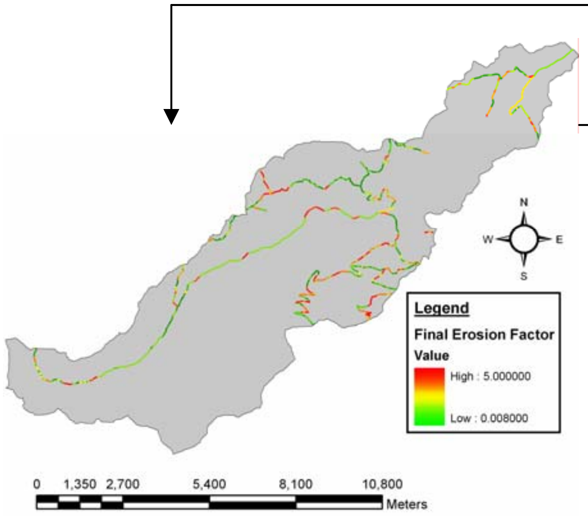
Value	Description
0.2 🟩	Low (<8%)
1 🟨	Moderate (8-12%)
2.5 🟥	High (>12%)

Road Class Segments

Value	Description
0.4 🟩	5180
1 🟩	1050
2 🟨	5150
0.5 🟧	960
1 🟧	1060
1 🟥	890

INTERSECTION

Final Erosion Factor = Positional Factor x Slope Factor x Class Factor



∑ Segment ... Segment 2 Segment 1 **Road Segment Length (Km)** × Segment ... Segment 2 Segment 1 **Final Erosion Factor**

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Final Watershed Road Impact Factor (RIF)

Figure 1. Flowchart depicting steps used to calculate the Road Impact Factor (RIF). Summation of Road Segment Length x Final Erosion Factor performed for each watershed

A mean travel time value was then calculated for each study watershed. This was performed by extracting only those travel time grid cells that intersect the watershed road segments, and averaging the travel time values.

Data Analysis

Quadrant Analysis

Preliminary testing performed on the effect of Road Impact Factor and Mean Travel Time on macroinvertebrate metrics was done using a "quadrant" approach (Figure 2). The quadrant partitions were created by utilizing the overall means of all watersheds for the respective parameters.

The hypothesized interaction between the two parameters being tested (RIF and Travel Time) and the value of the macroinvertebrate metric is straightforward. If a watershed has a high RIF value and a low Mean Travel Time value, placing it in the lower right quadrant, a lower macroinvertebrate metric value was expected due to the watershed having a high potential of road impact located close to the watershed outlet point (macroinvertebrate sample point). Conversely, if a watershed has a low RIF value and a high Mean Travel Time, placing it in the upper left quadrant, a higher macroinvertebrate metric value would be expected due to the watershed having lower potential road impacts located far from the watershed outlet point.

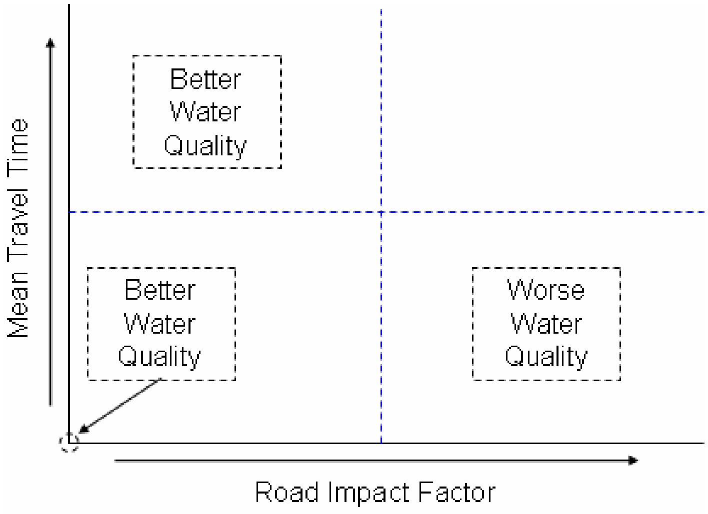


Figure 2. Quadrant analysis concept. Dashed lines represent quadrant breaks. Worse water quality located in SE quadrant; Better water quality in NW quadrant and at origin.

This trend would also be expected in watersheds with no roaded areas (points representing (0,0) on the quadrant graph). All other watersheds, with other parameter combinations (i.e. High RIF and High Mean Travel Time; Low RIF and Low Mean Travel Time) should represent moderately impacted watersheds. The fourth quartile (top 25%) of the individual metric values was used to represent the highest metric values. The first quartile (bottom 25%) of the individual metric values was used to represent the lowest metric values.

Hierarchical Clustering Analysis

Clustering Analysis was also performed on the dataset using the hierarchical clustering tool in SPSS (SPSS 2004). This study utilized the agglomerative clustering method to further understand the trends observed within the data set with the quadrant analysis. Euclidean distance was used as the distance measure in this analysis. The hierarchical clustering algorithm used was Ward's method. Ward's method is distinct from all the other clustering methods because it utilizes an analysis of variance approach to evaluate the distances between clusters. In short, this method attempts to minimize the Sum of Squares of any two (hypothetical) clusters that can be formed at each step and is regarded as very efficient.

Two hypotheses were tested for the clustering analysis utilizing the Road Impact Factor and Mean Travel Time parameters and the macroinvertebrate metrics:

1. Watershed condition (i.e. reference conditions) can be accurately classified using Road Impact Factor, Mean Travel Time, and individual macroinvertebrate metrics.
2. Macroinvertebrate metric values can be estimated by solely using Road Impact Factor and Mean Travel Time?

RESULTS

Quadrant Analysis

Several macroinvertebrate metrics values, in the Idaho study sites, exhibited trends similar to the original quadrant hypothesis (Figure 2). These macroinvertebrate metrics include *PLECT*, *KINTT*, and *EPHET*. *KTOLT* also exhibited a trend relating the 1st and 4th quartile metric values to Mean Travel Time and Road Impact Factor although it was opposite of the other metrics. This response was expected from *KTOLT* due to the inherent increase in tolerant taxa in disturbed conditions, which corresponds to high road impact factors in this study (Kerans and Karr, 1994).

The trends observed in the Idaho study sites appeared to be more closely correlated with Road Impact Factors than with Mean Travel Time. In other words, the vertical quadrant partitions (RIF) seemed to be more important that the horizontal partitions (Mean TT).

The Oregon study sites did not exhibit any trends that were as apparent as those in the Idaho study sites using the quadrant analysis approach. The differences observed in several of the metrics, including *KINTT* and *KTOLT*, appeared to be more correlated with Mean Travel Time than with Road Impact Factor. In other words, breaks between the 1st and 4th quartiles seem to follow a horizontal trend.

Clustering Analysis

Hypothesis 1

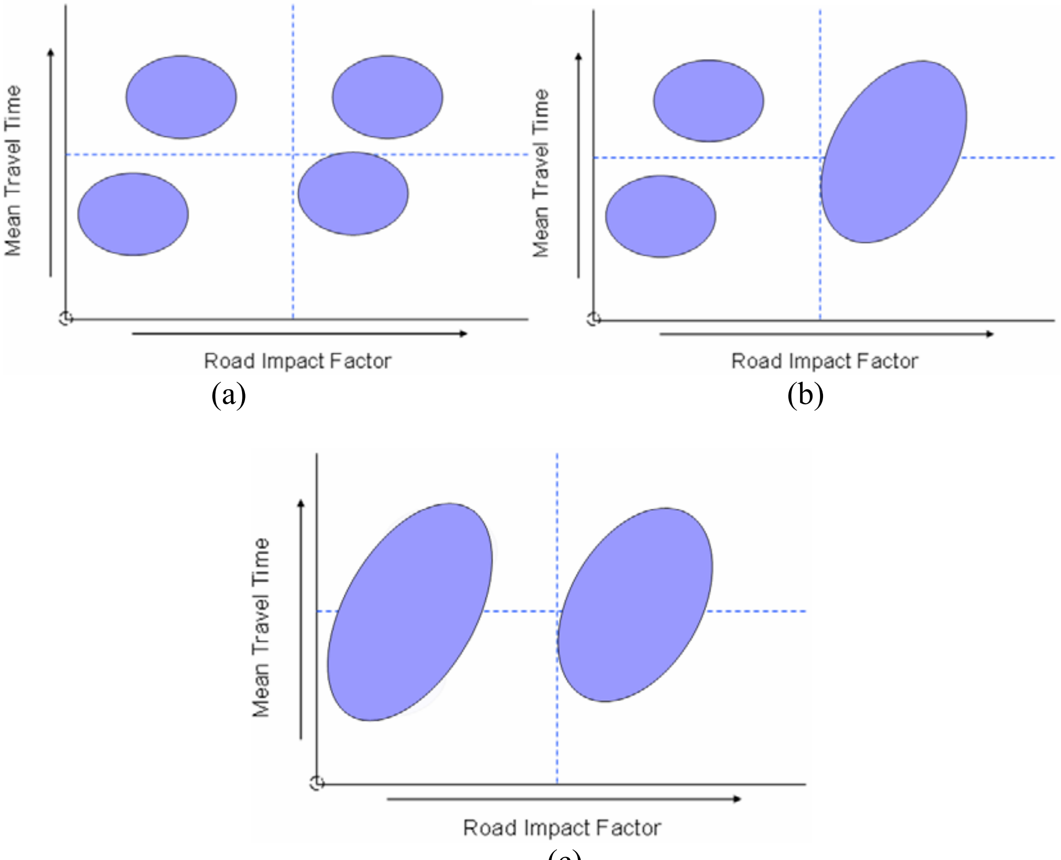
Two cluster assignments were chosen for this analysis. Each study site was assigned a cluster identification representing a 1 for non-reference or a 2 for reference conditions from the cluster analysis procedure. This methodology was utilized so that each study site could then be related back to the original reference or non-reference condition designation. An accuracy assessment, in the form of a contingency table analysis, was performed for each of the ten macroinvertebrate metrics to identify the extent to which the clustering analysis classification was correct.

In the Idaho study sites several metrics, when used in conjunction with Road Impact Factor and Mean Travel Time, correctly classified over 80% (*TV1, EPHET, %EPHEA, PLECT*) of the reference designations discussed earlier. This level of accuracy was deemed acceptable due to the high variability observed in this macroinvertebrate dataset. A comparative analysis was also performed using solely the Road Impact Factor and Mean Travel Time parameters (i.e. withholding all metric information), in order to assess whether or not adding an individual metric to the clustering analysis increased the overall classification accuracy. The classification accuracy in Idaho for the clustering using solely Road Impact Factor and Mean Travel Time was 63.04%. This provided evidence that the inclusion of *TV1*, *EPHET*, *%EPHEA*, and *PLECT* resulted in a significant increase in the accuracy of reference condition prediction.

In the Oregon study sites, however, none of the macroinvertebrate metrics measured exhibited the ability to correspond with watershed condition when coupled with Mean Travel Time and Road Impact Factor. The low classification accuracy ranged from 46.95% (*TV1*) to 65.31% (*KTOLT*). The classification accuracy for the clustering using solely Road Impact Factor and Mean Travel Time was only 53.06%. No clustering analysis accuracy exhibited significant improvement with the inclusion of a particular macroinvertebrate metric.

Hypothesis 2

Four cluster assignments were chosen for this analysis, designed to correspond with the four quadrants used in the quadrant analysis discussed above. The clusters for both Idaho and Oregon followed the quadrant breaks closely, indicating the utility of stratifying study sites based on these two input parameters (Figure 3a).



(a) (b)

(c)

Figure 3. Conceptual representation of the clustering process observed in both Idaho and Oregon as the number of classes decreased.

By decreasing the number of clusters in subsequent clustering analysis, a pattern of grouping was observed. All groups were consolidated vertically, denoting more similarity between the Mean Travel Time values of the groups. When 4 classes were utilized for the analysis, the clusters aligned fairly closely with the 4 quadrants (Figure 3a). By decreasing the number of classes to 3, the clusters in the NE and SE quadrants merged (Figure 3b). The clustering was fairly unaffected by the mean Travel Time quadrant breakline whereas it conformed to the Road Impact Factor quadrant breakline. As the number of classes was further decreased to 2, the clusters in the NW and SW quadrants merged (Figure 3c). Again, the clustering was significantly effected by the Road Impact Factor breakline.

DISCUSSION

Several of the metrics analyzed in the Idaho study sites displayed slight trends in accordance with hypothesized relationships with road impact stressors. Conversely, little correlation between road impacts and macroinvertebrate communities could be determined in the Oregon study sites. In order to obtain desirable results from a study such as this, the most accurate and detailed base data available (road data in this case) must be attained for inclusion into the model process. In Oregon, unfortunately, the most detailed road dataset was TIGER/Line data which is fairly general in regards to attribute detail and spatial accuracy. As with many GIS analyses, the data was the limiting factor in this study and was crucial to the success of the model.

The trends observed in this study may not, however, be significant enough to warrant the further use of this particular macroinvertebrate inventory dataset for watershed impact research. The macroinvertebrate inventory dataset utilized in this study is the product of an ongoing compilation by Dr. Vinson at Utah State University. Samples from hundreds of researchers and dozens of government agencies, all with varying knowledge, sampling techniques, and research goals were amassed into this centralized inventory database. Due to this compilation scheme, it was very challenging to acquire any signal from this dataset. As discussed above, a designed experiment would be better suited for this type of research.

The logical reasons for utilizing this GIS model still remain. The use of a Road Impact Factor model represents a reasonable way of approaching anthropogenic impact analysis, when compared to parameters currently used widely such as basic road density. The Road Impact Factor model takes numerous factors of road construction and development into account and can be performed on a regional scale. This model should not, however, be used as a method to predict stream water quality values through the use of road impacts within the watershed. It should rather be used as a way to categorize watersheds with respect to their potential for stream water impacts. Additional research should be performed to further understand this model's applicability as a watershed screening tool.

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